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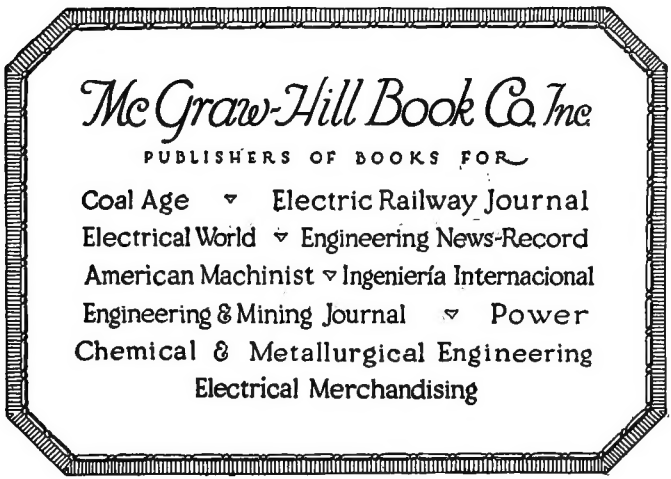
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GENERAL ECONOMIC GEOLOGY

A TEXTBOOK


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GENERAL ECONOMIC GEOLOGY

A TEXTBOOK

BY

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FIRST EDITION

McGRAW-HILL BOOK COMPANY, INC.
NEW YORK: 370 SEVENTH AVENUE
LONDON: 6 & 8 BOUVERIE ST., E. C. 4
1922

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THE MAPLE PRESS YORK PA

PREFACE

This volume is an introduction to the study of mineral deposits. It was prepared for students in colleges and technical schools who already have a knowledge of the elements of general geology and mineralogy. It embraces the geology of mineral fuels, structural materials, and other nonmetals and of the metals. The treatment is necessarily brief and might well be followed by specialized courses on coal and petroleum, and a more advanced course on the metals.

The order of treatment is indicated in the table of contents. The first chapter includes introductory matter, definitions, and an outline of classification of mineral deposits. It is followed by a treatment of coal, of petroleum and the solid bitumens. Then follows a more detailed discussion of the classification and genesis of mineral deposits which is succeeded by a section on nonmetals and one on metals. Coal, petroleum and bitumens might, perhaps equally well be included with the nonmetals and treated after the classification is systematically developed. In practice however, the plan followed here has a certain merit, and it is believed to be justified for that reason. A classification of mineral deposits is after all merely an instrument for study and for comparison of the deposits, and it is not particularly useful for the study of coal and petroleum. An advantage is gained also by treating these substances near the beginning of the course, because the salient features of the geology of coal are easier for the student to grasp than those of the geology of the metals, and the geology of petroleum can be treated advantageously apart from the systematic treatment of the metals and nonmetals. The sections on metals and nonmetals and on mineral fuels are so written that each is essentially independent of the others, and those on mineral fuels could be taken up last without much loss due to the arrangement if that seemed desirable to the instructor.

I gratefully acknowledge my indebtedness to Professors F. F. Grout, T. T. Quirke, and C. R. Stauffer and Messrs. G. M. Schwartz and John W. Gruner, who have read critically certain sections of the volume, and to Henry G. Schnobrich for assistance in the preparation of drawings. I have endeavored suitably to acknowledge the principal sources of information by footnote references.

W. H. Emmons.

Minneapolis, Minn.,
February 7, 1922.

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GENERAL ECONOMIC GEOLOGY

CHAPTER I

INTRODUCTION AND CLASSIFICATION

Scope of Economic Geology.—Economic geology is the application of geology to economic problems. It is sometimes termed mining geology or applied geology. It treats of the occurrence, distribution, and origin of mineral deposits. In general the economic geologist is expected to answer the questions: Where is the deposit? Why is it where it is? To what depth is it likely to extend? What changes are likely to take place in it with increasing depth? How shall one find the continuation of a deposit that is "lost"?

The practising economic geologist is expected to appraise mines and prospects or estimate their value and to recommend development work that will reveal at minimum cost any deposits that are not exposed. He is expected also to have a general knowledge of the distribution of deposits of the valuable minerals. Changes in mining, milling, and metallurgic practice are continually taking place and such changes may make it possible to treat at a satisfactory profit material that was formerly valueless. A few decades ago the introduction of the cyanide process made workable many deposits of gold-bearing rock that had previously been unworkable. Later the improvement of the cyanide process made certain silver-bearing deposits valuable. Still later the oil-flotation process made valuable ores of material that could not be treated before. These and other changes again and again have revived mining districts that were essentially abandoned. The geologist is frequently called upon for information about districts that are dormant.

Changes in trade and transportation are continually changing conditions for mining. The economic geologist is expected to be informed as new needs arise. When the European war was begun there was need for many metals. High-grade manganese

ore, tungsten ore, and many other ores that the United States had previously imported were sought for in this country. Later, when the shipping situation became acute, high-grade iron ore. chromium, tin, and other metals were sought for. Some of these ores were supplied from deposits which were well known but which had not been worked under normal conditions. Each year the geologist is called on more and more in connection with trade problems.

The great industrial centers are generally near the sources of raw materials. Most industries depend so much upon others that they cannot stand alone. Grain and livestock, coal and coke, acid and limestone, as well as the metals, pulp wood, and various chemicals are necessary for a highly diversified group of industries. This is illustrated[1] by Fig. 1, which shows some of the relations indicated.

The three chief chemical agents used in the industries are sulphuric acid, the most important industrial acid; lime, the chief alkali; and coke, the chief reducing agent. These are obtained respectively from sulphur and the sulphides; from limestone; and from coal. No district can reach a well-rounded industrial development, characterized by the greatest variety of bulky industrial products and by-products, unless it contains these resources or has means of obtaining them cheaply and in large quantities. They may be regarded as key blocks of the industrial arch. Without them it is generally necessary to export intermediate products, and industry suffers through the necessity of meeting transportation costs.

Economic geology is closely related to general and to structural geology. The problems that arise can best be solved by one who has an adequate knowledge of the structural and historical geology of the region containing the deposits, such as is gained by detailed mapping, together with an understanding of the genesis of the deposits, their relation to the structure, their deformation, and their superficial alteration and enrichment.

Deposits that have been precipitated from aqueous solutions in and along fractures in rocks receive but scant attention in the other branches of geologic science as now developed, and the

[1] This Chart was translated and is reproduced with modifications from one exhibited in the museum at Munich; it shows merely certain salient features of the relations of materials to industries. Other relations can readily be suggested.

study of such deposits is especially appropriate in the economic branch. Certain definitions, most of which refer to veins or to vein formation, are given below. The list is not exhaustive; the student is advised to refer to the index for other definitions that

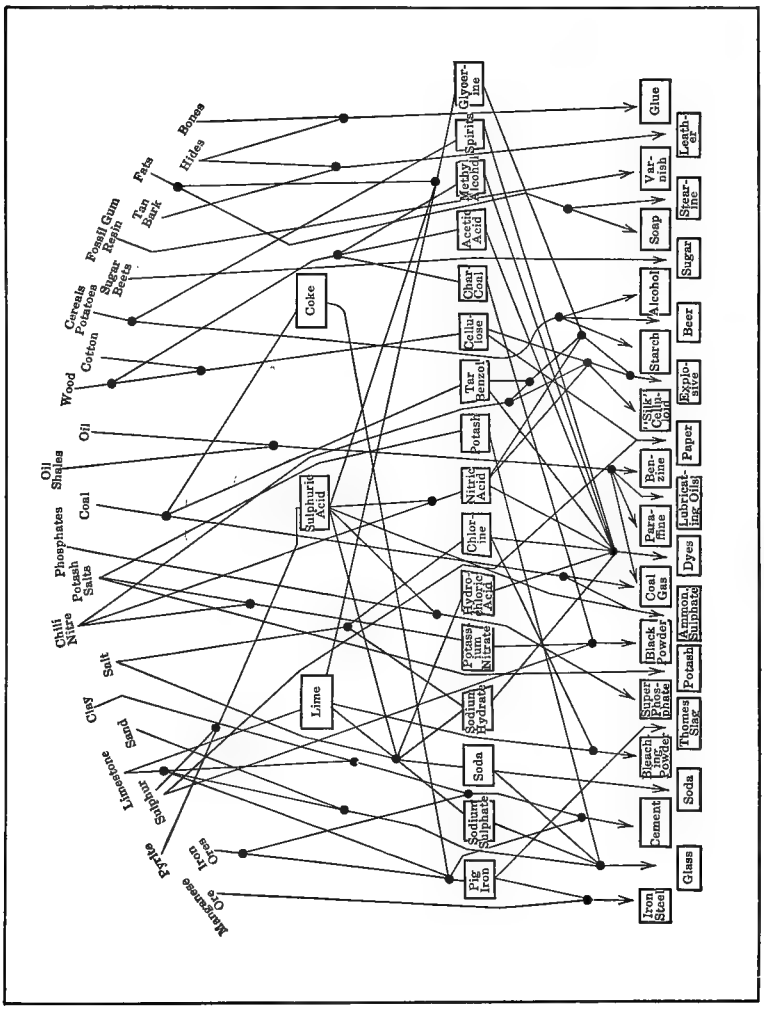


FIG. 1.—Chart illustrating some of the relations of certain raw materials to intermediate products. It shows the prominent positions of lime, sulphuric acid and coke.

are introduced at appropriate places in the text.

Definitions.—An *ore* is a mineral or association of minerals that may, under favorable conditions, be worked commercially for the extraction of one or more metals.

Protore is low-grade metalliferous material which is not itself valuable but from which valuable ore may be formed by superficial alteration and enrichment.

An *ore mineral* is one that contains a valuable metal.

A *gangue mineral* is an earthy or nonmetallic mineral associated with the ore minerals of a deposit.

A *tabular body* is shaped like a tablet, short in one and long in two dimensions.

A *vein* is a mineral mass, more or less tabular, deposited by solutions in or along a fracture or group of fractures. By some the term has been applied also to beds of coal and iron ore.

Country rock is the rock that incloses a deposit.

Vein walls are the rock surfaces on the borders of veins. If there is much replacement of the country rock along the fissure the ore may grade into the wall rock and its walls may be indistinct.

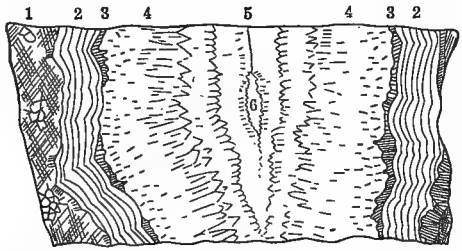


FIG. 2.—Section of part of amethyst vein, Creede, Colorado. It shows symmetrical crustified banding. 1, Chlorite, quartz, sphalerite and galena; 2, finely banded quartz; 3, sphalerite and a little quartz; 4, amethystine quartz; 5, union of quartz combs; 6, vug.

A *druse* or *vug* is an unfilled portion of a vein.

Banded ore is ore composed of bands or layers. The layers may be composed of the same minerals differing in color or texture or proportions, or they may be composed of different minerals.

Crustification or crustified banding is produced when mineral layers of different character are deposited successively one upon another on the borders of openings. In *comb structure* elongated prisms project approximately at right angles to a surface, like teeth of a comb.

Symmetrical banding results where solutions deposit similar material on both sides of an opening, layer on layer, as shown in Fig. 2.

Vein material is the matter that constitutes veins, whether ore or gangue, workable or not workable.

Gouge is soft clay-like material that occurs at some places as a

selvage between a vein and country rock. It is usually formed by the crushing of ore or country rock, or both.

Replacement is a process in the operation of which rocks and ores are slowly dissolved and material of different composition is deposited in the spaces which they occupied. Deposition follows solution closely so that forms and textures of earlier substances are often preserved.

The *paragenesis* of an ore expresses the relations of its minerals, especially the relations that bear upon its origin.

Hydrothermal alteration is a process by which rocks and ores are changed by hot waters.

Outline of Classification of Mineral Deposits.—Study of the genesis of a mineral deposit should recognize three groups of processes—those concerned in (1) deposition, (2) deformation, and (3) superficial alteration and enrichment of the deposits.

Minerals deposited by any process may be deformed by faulting, folding, and deep-seated metamorphism. Through processes of superficial alteration deposits may be enriched or impoverished. Deposits that exist essentially as they were originally formed are termed *primary* or *hypogene* deposits; those that have been altered by dynamic processes may be termed *deformed* deposits; and those that have been altered by superficial agencies are frequently referred to as *secondary* or *supergene* deposits. Part of a deposit may be primary and another part secondary. When metals are transferred either in solution or mechanically and deposited where there was no ore or protore before, the deposit is primary, whether it is a placer, a chemical sediment, or a vein.

CLASSIFICATION OF PRIMARY DEPOSITS

1. Deposits formed by magmatic segregation; consolidated from molten magmas.
2. Pegmatite veins; deposited by "aqueo-igneous" magmatic solutions.
3. Contact-metamorphic deposits; deposited in intruded rocks by fluids passing from consolidating intruding rocks.
4. Deposits of the deep vein zone; formed at high temperature and under great pressure, generally in and along fissures.
5. Deposits formed at moderate depths by ascending hot solutions.
6. Deposits formed at shallow depths by ascending hot solutions.
7. Deposits formed at moderate and shallow depths by cold meteoric solutions.
8. Sedimentary deposits; chemical, mechanical, organic, etc.

Syngenetic deposits are those formed contemporaneously with the inclosing rocks. They include deposits formed by magmatic segregation and sedimentary deposits.

Epigenetic deposits are formed later than the rocks that inclose them. They are deposited in openings in rocks, or by replacement.

Deposits formed by magmatic segregation are products of the differentiation of igneous magmas. They are in the strict sense igneous rocks. These deposits include ore bodies of considerable value, among them the great magnetite deposits of the Kiruna region, Sweden, and some of the magnetic iron ores of the Adirondack Mountains, in New York. No large sulphide deposits of this class are known in the United States. The nickel-copper deposits of Sudbury, Ontario, are the best-known examples of this group in North America.

In many places where igneous rocks rich in iron, nickel, or chromium minerals are weathered at the surface, especially under temperate or tropical conditions, the metals are concentrated, owing to the removal of other material. So prominent are the secondary processes in the genesis of such ores that they are classed by some as a distinct group, although the protores, or unworkable material from which the ores are derived by weathering, are igneous rocks.

Pegmatite veins are nearly related to deposits formed by magmatic segregation. They are end products of crystallization that have been thrust, like igneous dikes, into openings in rocks already consolidated. Pegmatites that have not moved from their parent magma and are not related to openings in rocks could properly be classed with syngenetic deposits, as deposits formed by magmatic segregation, but some authorities reserve the latter term for the more basic differentiation products. Pegmatites supply many valuable non-metallic substances and many gems. They are comparatively unimportant as sources of metals.

Contact-metamorphic deposits are formed at and near contacts of intruding and intruded rocks by fluids (liquids and gases) given off by intruding igneous magmas near by. They may generally be distinguished from lode deposits by their irregular shape and by their apparent independence of fissuring, together with the fairly constant association of the minerals they contain.

The deposits of the deep vein zone are mineralogically related

more or less closely to contact-metamorphic deposits. They have formed in and along openings in rocks, however, and in the main they are more nearly tabular in form than the contact-metamorphic deposits. As pointed out by Lindgren, who first defined the group, the deposits of the deep zone have formed under conditions of high temperature and pressure, which prevail also under conditions of contact metamorphism.

The deposits formed at moderate depths by ascending hot solutions constitute an important group. They differ from ores formed in the deep veins and from those formed at shallow depths in their mineral composition and in the character of the alteration of the wall rock accompanying their formation.

Deposits formed at shallow depths by ascending hot solutions are generally related to well-defined openings in rocks, such as fissures or to the intergranular spaces in conglomerates or sandstones or openings in vesicular lavas. These deposits may be distinguished from veins formed at moderate or greater depths by the minerals they contain and by the character of the alteration of their wall rocks.

The deposits formed at moderate and shallow depths by cold solutions include a large number of valuable deposits of lead and zinc in the Mississippi Valley and many small copper deposits in the Southwest. The deposits are formed by ground water that gathered its metallic contents from great masses of rocks in which the metals were sparingly disseminated. The metallic salts, chiefly sulphates, chlorides, and carbonates, were gathered in water channels, and the metals were deposited as sulphides where conditions were favorable. In many localities some form of organic material supplied the precipitating agent. If deposition had taken place on an older sulphide these deposits would be classed as secondary sulphide ores, but in general there is no evidence that bodies of older sulphide ore occupied the places of the deposits. These ores are therefore considered primary, although they have been leached by ground water from older metalliferous rocks.

Sedimentary beds of mechanical, organic, or chemical origin are the sources of many economic products, such as coal, clay, gypsum, salt, potash, lime, phosphate rock, iron, manganese, and placer gold. Workable sulphide deposits of sedimentary origin are rare. Sedimentary deposits, like sedimentary rocks, are derived mainly from the decay of older rocks and older deposits.

MINERAL PRODUCTS OF THE UNITED STATES AND LEADING PRODUCING STATES IN 1918 (*After Laughlin and Clark*)

Mineral	Principal producing States in order of value in 1918
Aluminum	New York, North Carolina, Tennessee.
Antimonial lead	Not separable by States.
Antimony ore	Nevada, Idaho, Alaska.
Arsenious oxide	Not separable by States.
Asbestos	Arizona, California, Maryland, Georgia.
Asphalt	California, Texas, Oklahoma, Illinois.
Barytes (crude)	Georgia, Missouri, Tennessee, Kentucky.
Bauxite	Arkansas, Georgia, Alabama, Tennessee.
Borates	California.
Bromine	Michigan, West Virginia, Ohio.
Cadmium	Not separable by States.
Calcium-magnesium chloride	Michigan, West Virginia, Ohio, California.
Cement	Pennsylvania, Indiana, Missouri, California.
Chromic iron ore	California, Oregon, Alaska, North Carolina.
Clay:	
Products	Ohio, Pennsylvania, New Jersey, Illinois.
Raw	Pennsylvania, Missouri, New Jersey, Ohio.
Coal:	
Bituminous	Pennsylvania, West Virginia, Illinois, Ohio.
Pennsylvania anthracite	Pennsylvania.
Coke	Pennsylvania, Ohio, Indiana, Alabama.
Copper	Arizona, Montana, Utah, Michigan.
Diatomaceous (infusorial) earth and tripoli	California, Illinois, Missouri, Pennsylvania.
Emery and corundum	New York, North Carolina, Virginia.
Feldspar	Maine, North Carolina, New York, Pennsylvania.
Ferroalloys	Pennsylvania, New York, Virginia, Alabama.
Fluorspar	Illinois, Kentucky, Colorado, New Mexico.
Fuller's earth	Florida, Texas, Georgia, Arkansas.
Garnet for abrasive purposes	New York, New Hampshire, North Carolina.
Gems and precious stones	Montana, Nevada, California, Arizona.
Gold	California, Colorado, Alaska, Nevada.
Graphite	Alabama, New York, Pennsylvania, Rhode Island.
Grindstones and pulpstones	Ohio, West Virginia, Michigan.
Gypsum	New York, Iowa, Michigan, Ohio.
Iron:	
Ore	Minnesota, Michigan, Alabama, New York.
Pig	Pennsylvania, Ohio, Illinois, Alabama.
Lead	Missouri, Idaho, Utah, Oklahoma.
Lime	Pennsylvania, Ohio, Missouri, Virginia.
Magnesite (crude)	Washington, California.
Manganese ore	Montana, California, Arizona, Nevada.
Manganiferous ore	Minnesota, Colorado, New Mexico, Virginia.
Mica	North Carolina, New Hampshire, Georgia, Virginia.
Millstones	North Carolina, Virginia, New York.
Mineral paints:	
Natural pigments	Canvass discontinued.
Zinc and lead pigments	Pennsylvania, Kansas, Missouri, Wisconsin.
Mineral waters	Wisconsin, New York, California, Maine.
Natural gas	West Virginia, Pennsylvania, Ohio, Oklahoma.
Natural-gas gasoline	Oklahoma, West Virginia, California, Pennsylvania.
Nickel	Not separable by States.
Oilstones, etc	Arkansas, Indiana, Ohio, Vermont.
Peat	New Jersey. Illinois, Massachusetts, California.
Petroleum	Oklahoma California, Kansas, Texas.
Phosphate rock	Florida, Tennessee, South Carolina, Kentucky.
Platinum and allied metals	California, Alaska, Wyoming, Nevada.
Potash (K_2O)	California, Nebraska, Utah, Wisconsin.
Pumice	Kansas, California, Nebraska.
Pyrite	Virginia, California, New York, Georgia.
Quicksilver	California, Texas, Nevada, Oregon.
Salt	Michigan, New York, Kansas, Ohio.
Sand and gravel	Pennsylvania, Ohio, Illinois, New Jersey.
Sand-lime brick	Michigan, Pennsylvania, Minnesota, New York.
Silica (quartz)	Connecticut, Maryland, Tennessee, Wisconsin.
Silver	Montana, Utah, Nevada, Idaho.
Slate	Pennsylvania, Vermont, Maine, Virginia.
Stone	Pennsylvania, Ohio, Vermont, Michigan.
Sulphur	Louisiana, Texas, Nevada, Colorado.
Talc and soapstone	New York, Vermont, Virginia, California.
Tin	Alaska, South Carolina, South Dakota.
Titanium ore (rutile)	Virginia.
Tungsten ore	California, Colorado, Nevada, South Dakota.
Uranium and vanadium minerals	Colorado, Utah, Wyoming, Nevada.
Zinc	Oklahoma, Montana, New Jersey, Missouri.

MINERAL-PRODUCING STATES AND THEIR LEADING MINERAL PRODUCTS IN 1918 (*After Laughlin and Clark*)

State	Principal mineral products in order of value in 1918
Alabama	Coal, iron ore, clay products, cement.
Alaska	Copper, gold, silver, coal.
Arizona	Copper, silver, gold, lead.
Arkansas	Coal, bauxite, clay products, natural gas.
California	Petroleum, gold, copper, natural gas.
Colorado	Coal, gold, zinc, silver.
Connecticut	Clay products, stone, lime, sand and gravel.
Delaware	Clay products, stone, sand and gravel, mineral waters.
District of Columbia	Clay products, sand-lime brick, stone, mineral waters.
Florida	Phosphate rock, fuller's earth, stone, clay products.
Georgia	Clay products, stone, iron ore, cement.
Idaho	Lead, silver, zinc, copper.
Illinois	Coal, petroleum, clay products, cement.
Indiana	Coal, cement, clay products, stone.
Iowa	Coal, cement, clay products, gypsum.
Kansas	Petroleum, coal, natural gas, zinc
Kentucky	Coal, petroleum, clay products, fluorspar.
Louisiana	Petroleum, sulphur, natural gas, natural-gas gasoline.
Maine	Stone, lime, clay products, slate.
Maryland	Coal, clay products, cement, sand and gravel.
Massachusetts	Stone, clay products, sand and gravel, lime.
Michigan	Iron ore, copper, salt, cement.
Minnesota	Iron ore, manganiferous ore, clay products, cement.
Mississippi	Clay products, sand and gravel, mineral waters, stone.
Missouri	Lead, coal, zinc, clay products.
Montana	Copper, zinc, silver, coal.
Nebraska	Potash (K_2O), clay products, stone, sand and gravel.
Nevada	Copper, silver, gold, lead.
New Hampshire	Stone, clay products, mica, sand and gravel.
New Jersey	Clay products, zinc, cement, sand and gravel.
New Mexico	Copper, coal, zinc, silver.
New York	Clay products, salt, cement, iron ore.
North Carolina	Clay products, stone, iron ore, mica.
North Dakota	Coal, clay products, mineral waters, sand-lime brick.
Ohio	Coal, clay products, natural gas, petroleum.
Oklahoma	Petroleum, zinc, natural-gas gasoline, coal.
Oregon	Gold, chromic iron ore, copper, cement.
Pennsylvania	Coal, clay products, natural gas, cement.
Rhode Island	Stone, clay products, graphite, mineral waters.
South Carolina	Clay products, stone, phosphate rock, mineral waters.
South Dakota	Gold, tungsten ore, silver, stone
Tennessee	Coal, zinc, copper, clay products.
Texas	Petroleum, sulphur, coal, natural gas.
Utah	Copper, coal, silver, lead.
Vermont	Stone, slate, talc and soapstone, lime.
Virginia	Coal, clay products, stone, lime.
Washington	Coal, cement, clay products, magnesite.
West Virginia	Coal, natural gas, petroleum, clay products.
Wisconsin	Zinc, iron ore, stone, mineral waters.
Wyoming	Coal, petroleum, iron ore, natural-gas gasoline.

CHAPTER II

COAL

General Statement.—Coal is carbonaceous mineral matter that is generally consolidated as a result of being buried in the earth. It is used principally for fuel. Coal is opaque, except in very thin slices, and is not crystalline. It varies in color from light-brown to black and in hardness from that of rotten wood to that indicated by $2\frac{1}{2}$ or 3 on the standard scale. There are many kinds of coal, practically all of them derived principally from plants.

The first stage in coal formation is the production of vegetable tissue. When dried, woody tissue contains about 49 per cent. of carbon, 0.5 per cent. of ash, 44 per cent. of oxygen, 6 per cent. of hydrogen, and a little nitrogen and sulphur. Vegetable tissue is largely cellulose ($C_6H_{10}O_5$), but it contains other compounds, and the proportion of carbon in the whole is considerably higher than in cellulose.

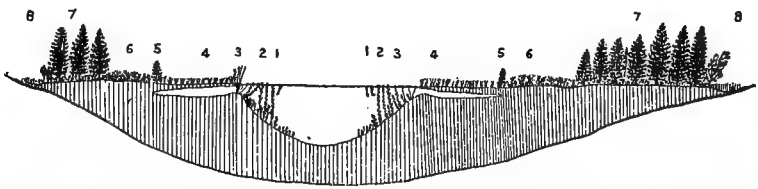


FIG. 3.—Diagram showing how plants fill depression from sides and top of a bog. 1, Zone of Chara and floating aquatics; 2, zone of Potamogetons; 3, zone of water lilies; 4, floating sedge mat; 5, advance conifers and shrubs; 6, shrub and sphagnum zone; 7, tamarack and spruce; 8, marginal fosse. (*After Davis.*)

The next stage[1] in the development of coal is the formation of peat. Mosses, grasses, and other plants grow, die, and are submerged and buried. On the surface of a bog are the growing plants; a little below the water surface, their recognizable remains; still deeper, a black, semigelatinous substance from which the vegetable structure has largely disappeared. This substance is peat (Fig. 3). Ultimate analyses of peat samples dried at 100° and calculated on an ash-free basis are stated on page 13.

[1] CLARK, F. W.: The Data of Geochemistry. U. S. Geol. Survey *Bull.* 616, p. 742, 1917.

Brown coal, or lignite, is mineral coal that generally retains the structure of the original wood. Some lignites are brownish-black, others are black.[1] Lignite is easily burned and gives a long smoky flame. It is high in moisture and low in heat value, dries out readily on exposure to air, tends to disintegrate (Fig. 4*a*) to a dark powdery mass, and slacks readily on burning. As a general rule lignites are found in the younger formations—that is, those of Cretaceous and Tertiary age. Jet is black, shining, dense lignite, prized because it can be carved into ornaments; much of it is probably derived from coniferous wood.

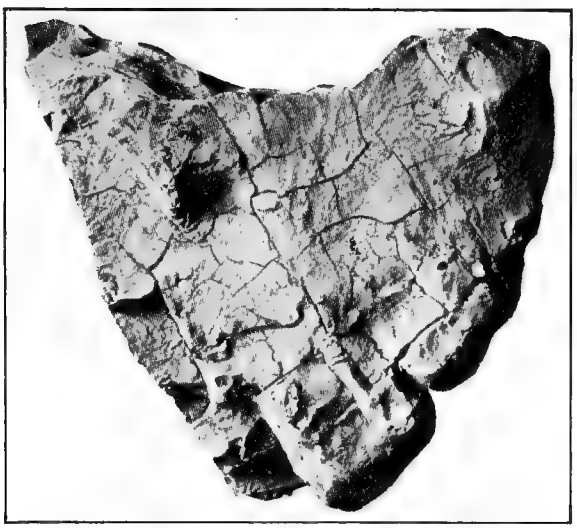


FIG. 4*a*.—Subbituminous coal, showing checking developed by drying. (*After M. R. Campbell.*)

Subbituminous coal is a grade between lignite and bituminous coal. In general it is black, and some of it has been called black lignite. It is more consolidated and less woody than lignite and is generally higher in moisture than bituminous coal. It checks[2] irregularly on drying, and on weathering it splits parallel to the bedding, whereas bituminous coal has a columnar cleavage. It slacks on burning.

[1] The present practice is to include black lignites with subbituminous coals.

[2] CAMPBELL, M. R.: A Practical Classification for Low-grade Coals. *Econ. Geol.*, vol. 3, pp. 134–142, 1908.

Bituminous coal is of higher rank than subbituminous—that is, it contains relatively more carbon. It also contains less water. On weathering it generally breaks across the layers, rarely along them. Bituminous coal rarely contains bitumen (p. 105). Reagents that dissolve the bitumens generally have

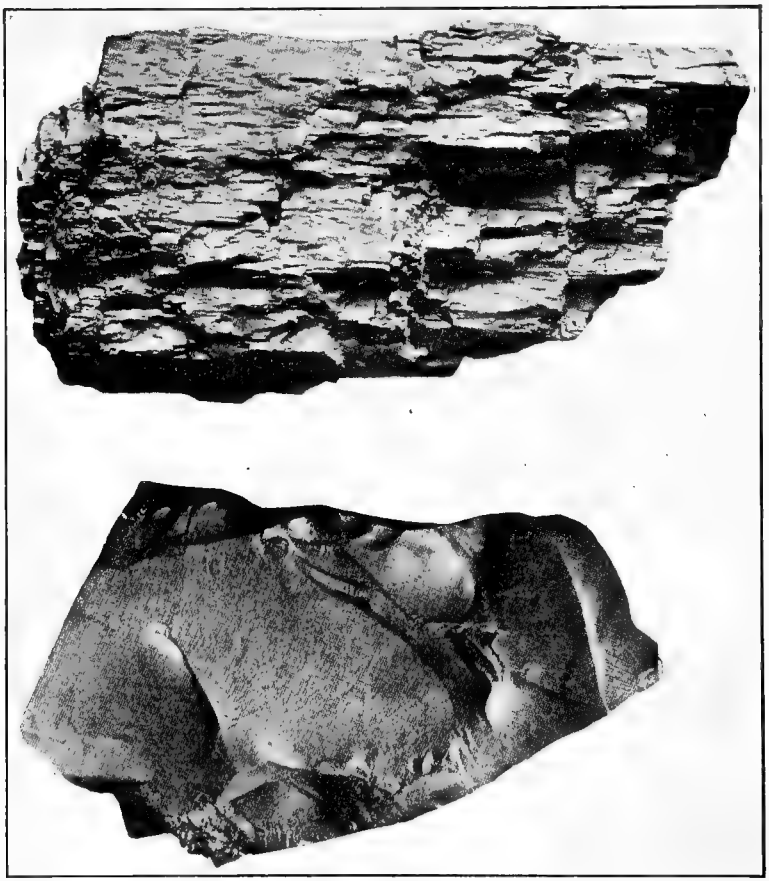


FIG. 4*b* (Upper).—Bituminous coal, showing prismatic structure. (*After Campbell.*)
FIG. 4*c* (Lower).—Cannel coal, shows conchoidal fracture. (*After Ashley.*)

no effect on the coals. Bituminous coal burns readily, with a yellow smoky flame. It has a higher heating power than lignite, does not disintegrate so readily on exposure (Fig. 4*b*), and withstands transportation better.

Chemically, bituminous coals represent a stage from lignite and subbituminous coals toward anthracite. They overlap

the subbituminous coals and there is no definite dividing line between. Analyses are stated on page 20.

ULTIMATE ANALYSES OF PEAT, COALS, AND ANTHRAXOLITE
(Ash, Moisture, and Sulphur thrown out)

	C	H	O	N
1. Light peat near surface	50.33	5.99	42.63	1.05
2. Heavy brown peat	62.54	6.81	29.24	1.41
3. Brown lignite	72.62	4.93	21.25	1.20
4. Subbituminous coal	77.47	5.44	15.34	1.75
5. Bituminous coal	81.87	5.85	10.92	1.36
6. Bituminous coal	84.19	5.82	8.57	1.42
7. Semibituminous coal	90.78	4.69	3.13	1.40
8. Semianthracite coal	91.47	4.25	2.64	1.64
9. Anthracite coal	93.90	3.22	1.88	1.00
10. Anthraxolite	96.69	.53	1.73	1.05

1, 2. CLARKE, F. W.: U. S. Geol. Survey *Bull.*, 616, p. 742.
3. Williston, N. D. *Idem*, p. 747.
4. Black lignite or subbituminous coal, Red Lodge, Mont. *Idem.*
5. Staunton, Ill. U. S. Geol. Survey *Bull.* 290, p. 63.
6. Vigo County, Ind., *Idem*, p. 109.
7. Ehrenfeld, Pa. *Bull.* 290, p. 179.
8. Coal Hill, Ark. U. S. Geol. Survey *Prof. Paper* 48, p. 202.
9. Scranton, Pa. *Idem*, p. 245.
10. Graphitic material from Sudbury, Ont. *Chem. News*, vol. 76, p. 186, 1897.

Semibituminous coal is a stage between bituminous coal and semianthracite. It is higher in carbon than bituminous coals and generally lower in volatile matter.

Semianthracite is a stage between semibituminous coal and anthracite.

Anthracite is a coal in which the transformation of vegetable matter has gone far. It is a hard black coal with bright luster, is brittle, and breaks with conchoidal fracture. It has a high percentage of fixed carbon and is low in volatile hydrocarbons. It ignites less readily than bituminous coal, burns with a short flame, and gives much heat with little smoke. It is esteemed highly as a domestic fuel.

Anthraxolite and graphitoid are coaly substances that have been metamorphosed beyond the anthracite stage.

Cannel coal (Fig. 4*c*) is a dull-black bituminous coal with a

conchoidal fracture; it ignites easily, burns readily, and is rich in volatile matter. Block coal is bituminous coal that breaks into square blocks. Stone coal and pit coal are terms commonly used in Great Britain for either bituminous coal or anthracite. Sea coal is coal transported by sea. Coking coal is bituminous coal that softens and becomes pasty in a fire; gases are driven off, and on quenching the coal becomes a coherent grayish-black cellular or fretted mass—coke. Gas coal is coal rich in gas. Splint coal is dull coal, high in ash. Carbonite, or native coke, is coal that has been distilled near intrusive igneous rocks. Bone, in coal, is hard material, shaly or somewhat sandy. It generally carries 33 per cent. or more of ash. Partings are beds of other rocks between coal layers.

Origin of Coal.—Coal is formed chiefly from peat that has been buried. It has partly decomposed and has been altered by heat and pressure. When woody material is buried it gives off certain gases—carbon dioxide (CO_2), carbon monoxide (CO), marsh gas (CH_4), and water. The chemical changes are indicated by comparison of analyses stated above, and by the following equations by Parr.[1] The composition of lignite, bituminous, and subbituminous coals is shown only in a general way. It is understood, of course, that the resulting substances are not simple chemical compounds, but complex mixtures, and that vegetable tissue is not all cellulose. The same transformation of cellulose to coal is illustrated by Fig. 5.

Vegetable Tissue		Loss by Decomposition					Coals
1. $5C_6H_{10}O_5$	=	$6CO_2$	+ CO +	$3CH_4$ +	$8H_2O$ +		$C_{20}H_{22}O_4$
Cellulose	=	Carbon oxides		Marsh gas	Water		Lignite
2. $6C_6H_{10}O_5$	=	$8CO_2$	+ CO +	$5CH_4$ +	$10H_2O$ +		$C_{22}H_{20}O_3$
Cellulose	=	Carbon oxides		Marsh gas	Water		Bituminous coal
3. $8C_6H_{10}O_5$	=	$10CO_2$	+ CO +	$7CH_4$ +	$18H_2O$ +		$C_{30}H_{16}O$
Cellulose	=	Carbon dioxide		Marsh gas	Water		Semi-bituminous coal

Peat is made up largely of cellulose and lignocellulose, the woody parts of plants, but it contains also the seeds, the mineral matter, and the nitrogenous material of plants, as well as any clay or sand washed into the bog during its formation. The peat is itself changed by decomposition before it is deeply buried. This decomposition is probably accomplished partly by bacterial

[1] Parr, S. W.: Composition and Character of Illinois Coals. Ill. Geol. Survey *Bull.* 3, pp. 27–69, 1906.

action. Bacilli have been found in peat bogs, and Renault[1] has identified their remains in coals. Where vegetable matter is not protected from air by water, it will rot or slowly become oxidized. Its constituent elements are returned to the air and are scattered. Decomposition under water, however, results in the preservation of a considerable part of the carbonaceous material and in concentration of carbon.

Briefly, conditions that are favorable for the formation of coal are (1) vegetation in a country of moderate relief, so that the low places are poorly drained and little sand and clay are washed into the area of growing plants; (2) abundant moisture so that the vegetation can be buried under water before it is oxidized; and (3) burial below later sediments before erosion removes the accumulated material.

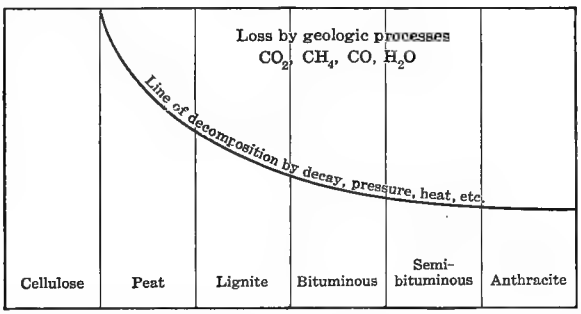


FIG. 5.—Diagram illustrating loss of CO_2, CH_4, CO and H_2O by decomposition of cellulose in process of forming coal. This diagram represents simplest changes possible. (*Adapted from Newberry.*)

Conditions 1 and 2 are now supplied in Minnesota, Wisconsin, Michigan, and other States in the northern part of the United States and in Canada where vast peat bogs are forming. About one-third of Minnesota is covered by peat, which at some places is 30 or 40 feet deep. The peat generally contains little clay or sand, and if it should become deeply buried under later sediments, in the course of geologic ages it would become coal.

It is believed that the plants that have formed coal are in the main fresh-water plants. That is shown by the fossil plants and animals found in coal beds. Some coals may have been formed from marine plants, but they are generally subordinate. In the

[1] RENAULT, B.: Soc. industrie minérale *Bull.*, 3d ser., vol. 13, p. 965, 1899, vol. 14, p. 1, 1900.

main rule the plants have grown where the coal beds are formed. This is shown by the stumps of trees standing upright, with their roots penetrating the ground below the coal bed. Such beds are termed *autochthonous*. Other coals have formed of material that has been transported; such coals are *allochthonous*. Most cannel coals belong to this class. They are composed largely of algæ and spores of plants that were washed into basins. They cover very small areas compared with their thickness. Some deposits of cannel coal have a thickness almost equal to their length or width.

The formation of peat and of coal is a slow process.[1] There are in Europe many peat bogs in which the occurrence of ancient works of art or architecture, whose approximate age may be determined, gives an opportunity to estimate the rate of growth. Rennie[2] reports a Roman causeway under 8 feet of peat. This shows that peat can grow at a rate of 1 foot in 200 years. Percy cites Roman roads under 36 feet of peat, which would require an annual growth of peat of about one-fifth of an inch.

Peat near the surface contains more water and less carbon than the peat deeper in the bog. The deep peat is partly decomposed and is more compact. As estimated by Ashley,[3] in a deep bog, such as must be postulated to yield the thick beds of coal, 1 foot of peat at the surface will later shrink to 3 inches owing to the loss of moisture; its loss by partial decomposition is about one-fourth of the vegetable matter of which it is composed, which leaves 2¼ inches, but as its specific gravity increases to about twice what it was before compression, the original 3 inches will be compressed to perhaps one-half, or to 1⅛ inches, and probably even less in very deep bogs. According to Ashley it takes about 10 years for a foot of surface peat to grow, or about a century for a foot of the buried peat. The weight of a cubic foot of peat from the lower part of the bed will average about 50 pounds. Deducting one-third of that weight for the loss of water and one-third of the remainder for the loss by distillation leaves about 22 pounds. A cubic foot of coal from the Appalachian field will on the average weigh about 87½ pounds;

[1] Ashley, G. H.: The Maximum Rate of Deposition of Coal. *Econ. Geol.*, vol. 2, pp. 34–47, 1907.

[2] Rennie, R.: "Essays on Natural History and Origin of Peat Moss," p. 40, London, 1907.

[3] *Op. cit.*, p. 39.

therefore, to make 1 foot of such coal will require about 4 feet of well-compressed peat. Thus it requires about 400 years for the growth of vegetable matter sufficient to form a foot of coal.

Ashley,[1] taking the maximum thickness of each coal bed, of the Carboniferous in the northern Appalachian field, found their sum to be 273 feet. For such thickness of coal to be formed would require more than 100,000 years.

Coals have been formed during many geologic periods other than the Carboniferous. Peats have grown in abundance probably since early Paleozoic time. During the Carboniferous period, however, physiographic conditions were especially favorable for their preservation.

Metamorphism of Coal Beds.—As has been stated, there is a progressive series of carbonaceous deposits consisting of peat, lignite, subbituminous coal, bituminous coal, anthracite, graphite. The place of a carbonaceous deposit in this series depends upon



FIG. 6.—Cross section northwest across Connellsville bituminous district near Connelsville, Pa. (*After M. R. Campbell.*)

the amount of metamorphism it has undergone. This conclusion is justified because the coals in certain formations are found to be of higher rank as mountains are approached, or where the beds are more intensely folded.

The great Appalachian coal field is in the Appalachian geosyncline, which lies west of the area of close folding of the Appalachian Mountains. In eastern Ohio and western Pennsylvania the coals are bituminous (Fig. 6). There is a gradual increase of carbon and a decrease of hydrocarbons from the west, where folding is slight, to the east, where it is greater. The anthracite region of Pennyslvania contains coals that are very closely folded (Fig. 7). These coals contain relatively little material except fixed carbon and ash. More metamorphosed still are the coals of the Rhode Island basin (Fig. 8).

Pressure due to deep burial also tends to increase the carbon content. The older coals, in general, are more metamorphosed

[1] ASHLEY, G. H.: The Maximum Deposition of Coal in the Appalachian Coal Field. *Econ. Geol.*, vol. 1, pp. 788–793, 1906.

than the younger ones and contain more carbon and less volatile matter.[1] Metamorphism, which alters coal, also either alters or destroys petroleum. Because of the close relation of the meta-

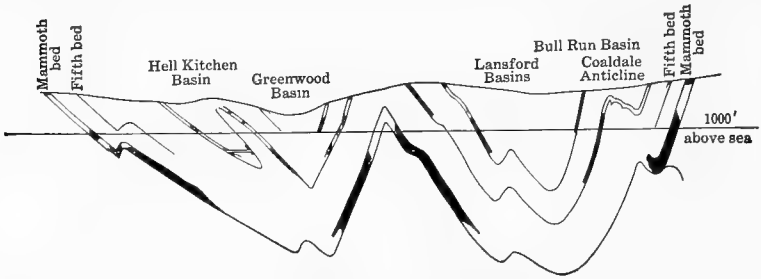


FIG. 7.—Section across the Panther Creek Basin, anthracite coal region, Pennsylvania. (*After Stoek.*)

morphism of coals as shown by their carbon ratios and the character of oils that may be present in the coal region, the carbon ratios in some regions have been studied with great interest (see Fig. 83, p. 130).

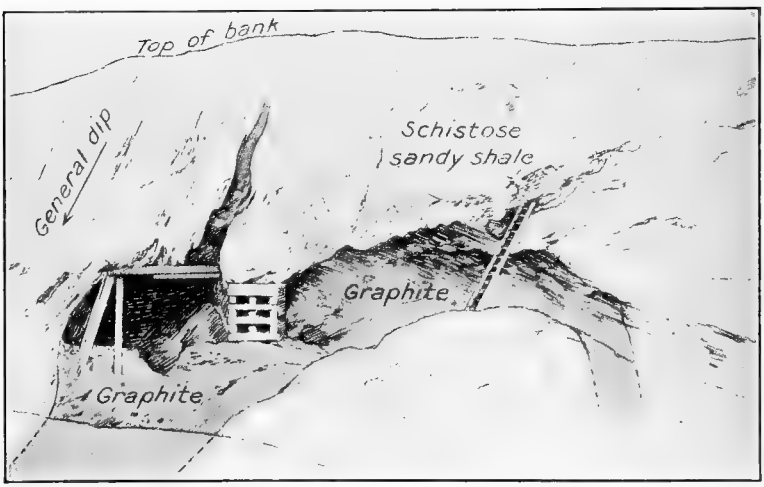


FIG. 8.—Diagram showing graphitic coal bed near Providence, R. I. The bed nearly pinches out above the present workings. (*After Ashley.*)

Peat is converted into coal by pressure and heat. Pressure may be due to weight of overlying rocks or to movements attending

[1] As shown on the following pages, there are noteworthy exceptions to this general rule.

deformation of the strata. Time is an important element, and in general, though not invariably the older coals are of higher carbon ratio than the younger ones. The changes are due to distillation, and the rate of distillation is important as well as the length of time during which the process has been operative. Some young coals near igneous rocks have been altered in a relatively short time. The anthracite and the bituminous coals of Pennsylvania are of the same age.

Distillation is due to heat,[1] which may be simply the heat of the earth, or heat generated by movements or by igneous activity. In general, the more deeply buried coals have been the warmer, as the earth's heat increases about 1°C. for every 100 feet downward. Metamorphism is aided by thrust as well as by the weight and permeability of the overlying load.[2] The extent of change depends partly upon the readiness with which the products of distillation can escape. If they are liberated as fast as they are formed the rate of change depends upon the amount of heat applied. If, however, the vegetable matter is held between impervious layers of rock and under great pressure, the gases can not readily form and consequently there will be less change.

The permeability of the cover depends on its original porosity and on the jointing and fissuring to which it has been subjected. According to Campbell regional coal metamorphism is influenced by crustal movements, largely through the formation of joints and cleavage planes. Old rocks, even those that lie flat are generally more jointed than young rocks.

That movements due to folding can not alone convert vegetable matter into bituminous coal is shown at many places. In the oil fields of Galicia lignite beds are found in closely folded strata that dip at higher angles than the beds in Mesozoic and Tertiary coal fields of the United States that yield good bituminous coal.

At some places during metamorphism the coal beds have been intensely squeezed, and apparently under great pressure coal is plastic. The thickness of a folded bed may vary greatly. Under

[1] Campbell, M. R.: Hypothesis to Account for the Transformation of Vegetable Matter into the Different Grades of Coal. *Econ. Geol.*, vol. 1, pp. 26–33, 1906.

[2] White, David: The Regional Devolatilization of Coal (Abstract), *Science*, new ser., vol. 32, p. 221, August 12, 1910; Geol. Soc. America *Bull.*, vol. 21, no. 4, p. 788, 1910.

PROXIMATE ANALYSES OF COALS [1]

	State	Bed or field	Water	Volatile matter	Fixed carbon	Ash	Fuel ratio
1. Anthracite	Pennsylvania	Mammoth	4.119	3.084	86.379	5.922	27.99
2. Anthracite	Pennsylvania	Primrose	3.541	3.716	81.590	10.654	21.93
3. Semianthracite	Maryland	Elk Garden	0.804	14.811	80.329	4.056	5.42
4. Semibituminous	Pennsylvania	Lower Kittanning	0.615	17.935	76.503	4.345	4.26
5. Semibituminous	Pennsylvania	Brookville	1.470	17.93	75.508	4.525	4.21
6. Semibituminous	West Virginia	Pocahontas	0.410	18.21	76.38	5.00	4.19
7. Bituminous	West Virginia	New River	1.000	25.30	69.17	4.53	2.34
8. Bituminous	Pennsylvania	Lower Freeport	1.050	33.15	58.405	6.10	1.76
9. Bituminous	Pennsylvania	Upper Freeport	0.890	34.10	56.088	4.99	1.64
10. Bituminous	Pennsylvania	Pittsburgh	.....	31.04	61.970	5.77	1.99
11. Bituminous	Pennsylvania	Pittsburgh	1.260	31.79	57.790	7.16	1.81
12. Bituminous	Ohio	Middle Kittanning	5.93	36.48	52.41	5.13	1.44
13. Bituminous	Tennessee	Jellico	4.40	31.56	61.87	1.86	1.96
14. Bituminous	Tennessee	Sewanee	.....	29.24	70.76	7.81	2.41
15. Bituminous	Alabama	Pratt	2.10	25.77	68.35	3.70	2.65
16. Bituminous	Michigan	Somers No. 1	7.79	34.74	52.58	4.89	1.51
17. Bituminous	Illinois	No. 7	5.50	39.50	54.60	5.40	1.38
18. Bituminous	Indiana	Brazil Block	13.82	35.16	49.96	1.06	1.42
19. Bituminous	Kentucky	Mühlenburg	.....	36.42	53.26	6.74	1.46
20. Bituminous	Missouri	Bevier	4.39	36.66	52.50	6.45	1.43
21. Bituminous	Iowa	Collins No. 6	7.48	39.52	45.54	8.44	1.15
22. Bituminous	Kansas	Osage	7.19	40.03	41.13	11.65	1.03
23. Bituminous	Oklahoma	McAlester	2.08	37.52	56.02	4.38	1.49
24. Semianthracite	Arkansas	Shinn Slope	1.058	8.41	75.434	11.75	8.96
25. Bituminous	North Texas	No. 1	2.00	31.47	56.32	8.15	1.79
26. Bituminous	Colorado	Raton	0.75	31.13	57.07	11.05	1.80
27. Bituminous	Colorado	Yampa	9.36	24.97	55.92	9.75	2.24
28. Bituminous	Colorado	Canyon City	6.21	31.32	52.47	11.1	1.65
29. Anthracite	Colorado	Grand River	0.59	6.59	88.82	4.00	13.47
30. Bituminous	Colorado	La Plata	0.82	37.25	55.72	6.05	1.50
31. Bituminous	Wyoming	Black Hills	8.58	44.36	37.12	9.95	0.84
32. Subbituminous	Wyoming	Sheridan	13.05	37.55	44.70	4.70	1.19
33. Bituminous	Wyoming	Rock Springs	8.2	36.0	51.9	3.80	1.44
34. Bituminous	Montana	Great Falls	4.1	26.7	50.8	18.4	1.9
35. Subbituminous	Montana	Bull Mountain	9.4	31.2	52.8	6.6	1.69
36. Subbituminous	Montana	Eastern	19.0	35.6	37.0	8.4	1.04
37. Bituminous	British Columbia	Fernie	1.9	25.1	64.9	9.9	2.58
38. Subbituminous	New Mexico	Gallup	12.14	32.81	47.63	7.42	1.45
39. Bituminous	Washington	Wilkeson	0.70	23.545	56.895	18.715	2.41
40. Bituminous	Washington	Roslyn	1.45	32.794	35.656	11.944	1.63
41. Cannel	Texas	Rio Grande	2.26	48.64	36.15	12.95	0.74
42. Lignite	North Dakota	Williston	12.01	40.62	39.36	8.01	0.97

[1] See p. 28.

1. STOEK: Average of Five Specimens from Eastern Middle Basin. U. S. Geol. Survey *Twenty-second Ann. Rept.*, part 3, p. 72, 1902.
2. Average of Two Specimens from Western Middle Basin. *Idem.*
3. WHITE, DAVID: *Idem*, p. 211.
4. WHITE AND CAMPBELL: Ben Creek, Cambria County, Pa. *Idem*, p. 183.
5. Conemaugh, Cambria County, Pa. *Idem*, p. 183.
6. WHITE, I. C.: Pocahontas No. 3. W. Va. Geol. Survey, vol. 2*a*, p. 145, 1908.
7. WHITE, I. C.: New River Valley Mine, New River Coal, South Side of New River, Gaymont, Fayette County, W. Va. *Idem*, p. 215. This coal has been classed also as semi-bituminous.
8. Jefferson County, Pennsylvania. *Idem*, p. 184.
9. Westmoreland County, Pennsylvania. U. S. Geol. Survey *Twenty-second Ann. Rept.*, Part 3, p. 185, 1902.
10. Connellsville Basin, Fayette County, Pennsylvania. *Idem*, p. 185.
11. Connellsville Basin, Fayette and Westmoreland Counties, Pennsylvania. *Idem*, p. 185.
12. HAZELTINE: Middle Kittanning, Hocking Valley, Ohio. *Idem*, p. 221.
13. HAYES: Jellico, Campbell County, Tenn. *Idem*, p. 254.
14. Whitwell, Marion County, Tenn. *Idem*, p. 255.
15. Birmingham, Jefferson County, Tenn. *Idem*, p. 254.
16. LANE, A. C.: St. Charles, Mich. *Op. cit.*, p. 322.
17. ASHLEY, G. H.: St. Clair County, Illinois, Belleville Mine. *Idem*, p. 288
18. Brazil Block No. 1 Shaft, Brazil Block Coal Co. Ind. Geol. Survey *Twenty-first Ann. Rept.*, p. 106.
19. Eleven Analyses. Ky. Geol. Survey, see Ashley. U. S. Geol. Survey *Twenty-second Ann. Revt.*, part 3, p. 287.
20. BAIN: K. and T., No. 43. U. S. Geol. Survey *Twenty-second Ann. Rept.*, part 3, p. 347, 1902.
21. BAIN: Fort Dodge, Iowa. *Idem*, p. 347.
22. Kansas Univ. Geol. Survey, vol. 3, Special report on coal. p. 280, 1898.
23. TAFF: One Mile West of McAlester, Okla. U. S. Geol. Survey *Twenty-second Ann. Rept.*, part 3, p. 384, 1908.
24. Pope County, Arkansas. *Idem*, p. 396.
25. TAFF: Bridgeport, Wise County, Colo. U. S. Geol. Survey *Twenty-second Ann. Rept.*, part 3, p. 408, 1902.
26. STORRS: Coking Coal. *Idem*, p. 424.
27. GALE: Dry Creek 5-foot Seam, Yampa Field. U. S. Geol. Survey *Bull.* 297, p. 86, 1906.
28. STORRS: Canyon City Semibituminous. U. S. Geol. Survey *Twenty-second Ann. Rept.*, part 3, p. 424, 1902.
29. STORRS: *Idem*, p. 424.
30. STORRS: *Idem*, p. 424.
31. STORRS: *Idem*, p. 424. The fuel ratio of this coal is a trifle below the limit set down on Page 31, namely 0.92.
32. STORRS: *Idem*, p. 425.
33, 34, 35; STEBINGER: Am. Inst. Min. Eng. *Trans.*, vol. 46, p. 903, 1913.
36. STEBINGER: Eastern Montana Field. *Idem*, p. 903.
37. STEBINGER: Crow's Nest, From Dept. of Mines, Canada. *Idem.*
38. STORRS: U. S. Geol. Survey *Twenty-second Ann. Rept.*, part 3, p. 425, 1902.
39. SMITH, G. O.: U. S. Geol. Survey *Twenty-second Ann. Rept.*, part 3, p. 490, 1901.
40. *Idem*, p. 490.
41. VAUGHAN: Rio Grande Coal & Irrigation Co., Upper Bench. U. S. Geol. Survey *Bull.* 164, p. 64, 1900.
42. WILLSTON: Brown Lignite, North Dakota, No. 2. U. S. Geol. Survey *Prof. paper* 48, p. 243, 1906.

some conditions the coal has apparently become locally of purer quality. This has been pointed out by C. H. Clapp and is shown on Vancouver Island, where upper Cretaceous coals of fair quality are mined.[1] The principal coal fields are the Nanaimo field, near Ladysmith, in the southern part of the island, and the Comox field, about 65 miles northwest of it. The coals are, in the Nanaimo series, of Upper Cretaceous age. In the Nanaimo field there are three seams. These, as stated by Clapp,[2] are remarkably persistent, but vary greatly in thickness and quality. In places a variation as great as from 2 or 3 feet of dirty slickensided coal or "rash" to 30 feet of clean coal occurs within a lateral distance of 100 feet. This extreme variation probably is due to a folding of dirty or silty coal seams, when at least the clean coal, according to Clapp, was in a plastic or pasty condition that permitted it to flow to the parts of the folds, where there was a decrease of pressure.

Metamorphism may be carried to a point where the coal becomes unsatisfactory as a fuel. The coal of Rhode Island, which is of the same geologic age as the Pennsylvania coals, is so much metamorphosed that it is not readily inflammable, and it is a subject of discussion whether some of the Rhode Island coal is better suited for fuel or refractory material. In the Rhode Island field crushing, squeezing, and shearing have been intense and the accompanying heat high. As a result of this intense pressure and heat the coal has been changed to anthracite containing a high percentage of fixed carbon,[3] and in places the material of the beds has flowed, like so much putty squeezed in the hand, until the original structure is practically lost and nearly all of the combined carbon and hydrogen have been driven off, so that there the material has reached the last stage and become graphite[4] (Fig. 8). In Rhode Island, shales associated with the coal have yielded similarly under metamorphism, but to a less extent.

Igneous metamorphism may convert coal to coke, to anthracite, or to graphite (p. 319).

[1] Clapp, C. H.: Southern Vancouver Island. Canada Geol. Survey *Mem.* 13, pp. 124–133, 1912.

[2] Clapp, C. H.: Geology of the Nanaimo Map-area. Canada Geol. Survey *Mem.* 51, p. 97, 1914.

[3] See p. 28.

[4] Ashley, G. H.: Rhode Island Coal. U. S. Geol. Survey *Bull.* 615, p. 17, 1915.

Structural Features of Coal Deposits.—Coal beds range in thickness from mere seams to deposits 20 feet thick or more. Some cover only a few acres; others extend over thousands of square miles. There are few if any deposits of the other more valuable minerals that are found in bodies equal in size to the more extensive coal beds. Some coal beds lie flat; others are steeply tilted. They partake of the structure of the rocks that contain them. As most coals have been deposited in fresh water or in shallow marshes, they are generally associated with sediments deposited in shallow water, namely sandstones and shales or clays.

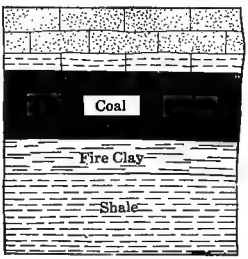


FIG. 9.—Section showing coal bed above a bed of fire clay.

The materials from which coal beds are formed are often laid down unconformably; hence coal may be found resting on limestone or any other rock, although it is not common to find limestone either directly below or directly above a coal bed. At a great many places clay or clay shale is found below the coal beds. Such clays at many places have been leached by ground water or by growing vegetation or both, and the more soluble constituents, such as alkalies and alkaline earths, have been removed from some of them. Such clays are therefore refractory and are commonly used as fireclays (Fig. 9). The majority of coal beds are covered by shale. Coal beds show bedding,

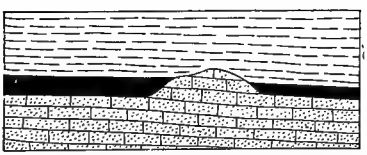


FIG. 10.—Diagram showing a "cut out" of coal bed due to its deposition on an uneven surface.

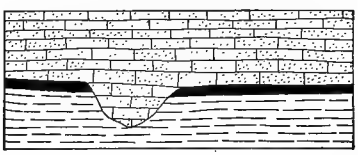


FIG. 11.—Diagram showing a "cut out" in coal bed due to erosion of coal and subsequent filling of channel by later beds.

lamination, and other features common to sedimentary rocks. In many places the coal bed is cut out, particularly where it has been deposited on an uneven surface (Fig. 10) or where it has been eroded before the cap rock was deposited (Fig. 11). Coal

beds contain "splits," or places where the bed separates. Such splits may be due to wedges of shale (Fig. 12) or to overthrusts



FIG. 12.—Diagram illustrating a "split" in a coal bed due to a wedge of shale.

(Fig. 13). Coal beds pinch out and swell, owing to movement and also to irregularity of deposition (Fig. 14).

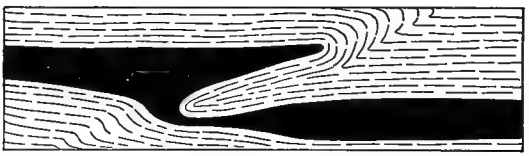


FIG. 13.—Diagram illustrating a "split" in a coal bed due to an overthrust.

Where a coal bed is underlain by clay that is not thoroughly compacted the clay tends to rise owing to pressure of overlying

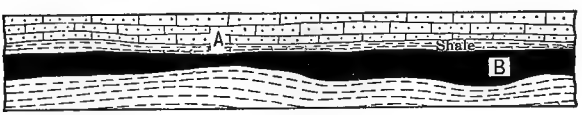


FIG. 14.—Section of coal bed showing "pinch" (*A*) and "swell" (*B*).

load. The clay may "creep" into galleries opened by mining or into cracks and joints in the coal, forming "horsebacks"

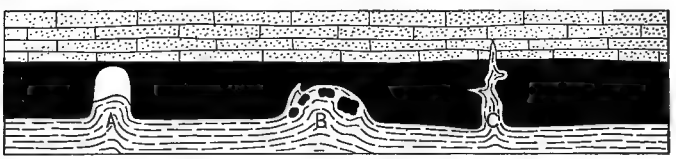


FIG. 15.—Diagram showing coal bed with (*a*) "creep" of underlying clay floor partly filling a gallery; (*b*) "horseback" or upward bulge of clay in floor; (*c*) "finger" or "crevice" filled with clay.

(Fig. 15). In certain bituminous coal fields these features are

common. In many Kansas fields blocks of coal are involved in the clay of the horsebacks.[1]

Some "horsebacks" are found to extend downward from the roof (Fig. 16).

Faults are common in coal mines. At some places the faults are so closely spaced that the coals can not be profitably mined.

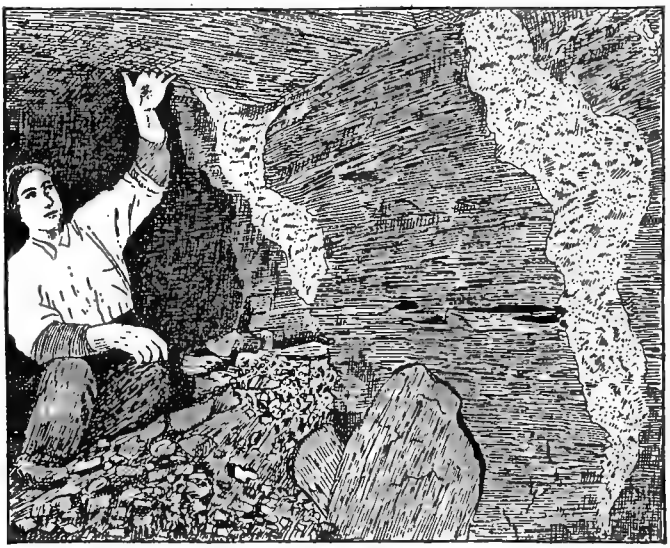


FIG. 16.—"Horseback" in mine at Weir City, Kansas.
(*After Haworth and Crane.*)

Outcrops of Coal Beds.—The outcrops of coal beds are generally marked by a "smut" or "blossom" of coal, resulting from a mixture of disintegrated coal with soil. This is more pronounced with lignite and bituminous coal than with coal of higher grades. Elements of the coal are slowly oxidized on contact with air. The weight is generally increased,[2] and the quantity of carbon and disposable hydrogen (see p. 28) is diminished. Thus the heat value of the coal becomes lower at the outcrop. Pyrite oxidizes and increases the weight of the coal and as this reaction gives up heat it facilitates the oxidation of other elements in the coal.

[1] HAWORTH, ERASMUS, and CRANE, W. R.: Special Report on Coal. Kan. Geol. Survey, vol. 3, p. 210, 1898.

[2] KIMBALL, J. P.: Atmospheric Oxidation or Weathering of Coal. Am. Inst. Min. Eng. *Trans.*, vol. 8, pp. 204–225, 1880.

Kimball,[1] as a result of observations in the Appalachian coal fields, concludes that the outcrops of almost all coal deposits have suffered deterioration. Many coking coals lose their power to coke. Screenings outside of mines and gob in mines often ignite spontaneously from the heat released through oxidation.

Anthracite suffers very little by weathering, except in the oxidation of its pyrite. Block coals and noncoking bituminous coals likewise suffer comparatively little loss. Coking coals lose in calorific value and in coking qualities, which are very closely related to the disposable hydrogen contained in the coal (p. 28). Coking coal exposed in pillars of mines only two or three years has been found to make unsatisfactory coke.

According to Catlett,[2] the outcrop of a coal bed is generally higher in ash than the coal 50 to 60 feet below the surface. The decrease of volatile constituents through weathering decreases the fuel value of the coal. A weathered coal may be expected to improve with increasing depth. A shaly material that is black and friable, however, will generally pass into a bony inferior coal.

Schultz has studied the weathering of coals in arid countries. In the Rock Springs field, Wyoming, he found practically no deterioration in the lower part of the zone of weathering above the ground-water level. This immunity he attributes to the presence of clay and shale, which shuts out the oxygen from the coal almost as effectively as ground water. In the upper part of the zone of weathering, however, the coal showed much deterioration.[3]

Notwithstanding the fact that coal deteriorates by exposure to weather, the deterioration is often slight and coals are mined at many places by stripping and loading with steam shovels. The coals are changed so little that they find ready sale for fuel.

Many coal beds are found above fire clay. Owing to the swelling of fire clay on removal of pressure through erosion of overlying beds there is a tendency for it to push up the outcrop of the coal, making it dip slightly near the surface, whereas it may be flat lying a few feet below.

[1] KIMBALL, J. P.: *Op. cit.*, p. 220.

[2] CATLETT, CHARLES: Coal Outcrops. Am. Inst. Min. Eng. *Trans.*, vol. 30, pp. 559–566, 1900.

[3] SCHULZ, A. R.: Weathering of Coal in the Arid Region of the Green River Basin, Sweetwater County, Wyoming. U. S. Geol. Survey *Bull.* 381, pp. 282–296, 1910.

Weathering of Coals in Storage.—The weathering of coals in storage is of interest not only to those who take samples of coal beds but to those who store coal for future use. Coal under water loses little or no heat value,[1] but exposure to air results in loss in a few months. Some coals ignite spontaneously when stored. Anthracite withstands storage better than bituminous coals, especially the tender bituminous coals. Pyrite oxidizes readily, especially if the coal is moist. The oxidation of pyrite may heat the coal stored, and it is attended by swelling, which causes the coal to disintegrate. As stated by Parr and Hamilton, outdoor exposure results in a loss of heating value of 2 to 10 per cent. and the loss is complete as a rule within 5 months; from the seventh to the ninth month the loss is inappreciable. Dry storage has no advantage over storage in the open except for high-sulphur coals, in which the disintegrating effect of the sulphur in process of oxidation facilitates the escape or oxidation of hydrocarbons.

Sampling of Coal Beds.—Samples of a coal bed should be obtained by cutting a channel across a clean face of the bed or across the bench or benches that it is desirable to test, including everything except partings and binders over ¼ inch in thickness and lenses and concretions greater than 2 inches in diameter and ½ inch thick. Five pounds of coal should be taken for each foot of the bed, and the material should be caught on a cloth to keep it clean and dry. The material should be broken in the mine to pieces not over ¼ inch in dimensions, and quartered on the cloth. Opposite quarters are thrown out and the material is mixed and quartered again until the sample is reduced to a quart, which should be placed in a can and sealed.[2]

Methods of Making Analyses of Coals.—Two methods are practised for the analysis of coals, namely the ultimate and proximate. In the ultimate method of analysis the amounts of carbon, hydrogen, oxygen, nitrogen, sulphur, and ash are determined, and if the coal is to be used for metallurgic fuel the ash also is analyzed. This method is useful in connection with the study of the origin and nature of the coal, but it is tedious and expensive and it does not always give all the information desired. It does not indicate the purpose for which the coal is adapted so well as the proximate method.

[1] Parr, S. W., and Hamilton, N. D.: The Weathering of Coal. *Econ. Geol.*, vol. 2, pp. 693–703, 1907.

[2] Campbell, M. R.: U. S. Geol. Survey *Bull.* 316, p. 251, 1906.
U. S. Bureau of Mines *Bull.* 22, p. 324, 1913.

The proximate analysis shows the amounts of moisture, volatile matter, fixed carbon, and ash. Usually the sulphur and sometimes the phosphorus are also determined. In making the proximate analysis[1] the moisture present is determined by exposing the weighed powdered sample in a platinum crucible one hour at a temperature between 104° and 107°C. The sample is then heated at red heat in absence of air for 7 minutes. This drives off volatile matter. In this test coking coal will fuse to a spongy mass. The crucible will then contain fixed carbon and ash, which are known as coke. A sample is ignited in air and burned, and the unburned portion is determined as ash.

The proximate analysis shows approximately the amount of coke that may be made from a coal and the amount of gases that it will give off. The fuel ratio is the percentage of fixed carbon divided by the percentage of volatile matter. The sum of fixed carbon and volatile matter indicates its fuel value or fuel percentage. The gases, however, will differ as to heat value, and this difference is not shown by the proximate analysis. If an ultimate analysis is available it is assumed that the oxygen will combine with the hydrogen to form water (H_2O) as long as any oxygen is present. The amount of hydrogen required for the reaction is designated "combined" hydrogen, and that remaining is "disposable" hydrogen. The disposable hydrogen is calculated by subtracting from the total hydrogen one-eighth of the percentage of oxygen present. The heat value of a coal is determined in the calorimeter, or less accurately by calculation from analyses.[2]

When coal is heated to 107°C. to drive off moisture, the water that is combined in kaolin, mica, iron oxides, and certain other minerals that may be present will not be driven off. It will be driven off, however, at higher temperatures with volatile matter.

Moisture is undesirable in coal. It represents useless material that must be mined and transported, and it takes a certain amount of heat to evaporate the water when the coal is burned. The quantity of water in coal varies greatly. In anthracite it

[1] Noyes, W. A., and others: Coal Analyses, Report of the Joint Committee of the American Society for Testing Materials and the American Chemical Society. *Jour. Ind. and Eng. Chem.*, vol. 9, pp. 100–107, 1917.

[2] Ralston, O. C.: The Relation of Calorific Value of Coal to Ultimate Analyses. U. S. Bur. Mines *Tech. Paper* 93, pp. 21–22, 1915.

may be only 2 per cent. or less. In bituminous coal it is commonly from 1 to 12 per cent.; in some lignites it is 20 per cent. or more. In general moisture is higher in coals that have high volatile matter, although some coals, which have very high percentages of volatile matter, contains little moisture. This is true particularly of many cannel coals.

The ash is approximately the mineral matter that was present in the vegetation that formed the coal, plus that which washed into the vegetation or was precipitated in it during or after formation, and the waste that was mined from the walls and partings of the coal bed, minus any mineral material dissolved and removed during the formation of the coal or later. Potash, soda, and alkaline-earth compounds are commonly removed as well as some of the iron. The ash in coal is of course objectionable, for it is essentially waste material that must be transported and disposed of after burning. In coking coals high ash is especially objectionable, as it must be slagged off in furnace or smelter charges. If it contains much phosphorus it is still more objectionable for smelting iron in blast furnaces. A coal with a fusible ash will form clinkers. Much lime and iron will generally make a fusible ash.

Coals contain sulphur in three forms—pyrite and marcasite, gypsum, and organic sulphur compounds. These compounds are objectionable because the sulphur gases corrode boilers, coal gas containing sulphur compounds is foul smelling, and coke containing sulphur is objectionable for iron smelting.

When coal is heated to a high temperature in a sealed retort the hydrocarbons are driven off as gas, leaving a residue of carbon and ash. The volatile matter is a complex mixture of CO_2, CH_4, H_2O, and many other substances. The amount and composition of the volatile hydrocarbons depend in a measure on the treatment of the coal, especially on the temperature of distillation.

Gas, tar, and ammonia are derived from coal in the process of making coke. Tar and ammonia are used for making dyes, medicines, explosives, and many other chemicals. These are indicated in Fig. 17. The utilization of the products derived from making coke is the basis of many industries.

Coke is used as a domestic fuel and for smelting metals. To be valuable for metallurgic purposes coke should be low in ash and phosphorus. It should stand up well during transportation and

should be strong enough to bear a burden of ore in a smelter so that the blast of air may be blown through the charge. Coke can be made only from coking coals or those that soften and become pasty in a fire.[1]

The heating value of coal is measured by the number of calories or British thermal units developed when a unit weight of the coal is burned. Expressed in calories it is the number of grams of water whose temperature can be raised 1°C. (from 0°C. to 1°C.) by the heat from the combustion of 1 gram of coal. Expressed in British thermal units (B.T.U.) it is the number of pounds of water whose temperature can be raised 1°F. by the heat of combustion of 1 pound of coal.[2]

As to the classification of coal by analysis, no hard and fast rules can be laid down that will apply to all coals. The fuel ratio is the fixed carbon divided by the volatile hydrocarbon. If the analysis of the coal is recalculated on an ash-free, water-free basis, the following relations[3] will generally hold.

[1] The following is a field test for coal to ascertain its coking qualities: Pulverize in an agate mortar a small quantity of the coal to be tested until it will pass through a 100-mesh sieve. Pour out the pulverized coal and observe the condition of the mortar and pestle. With some coals the mortar and pestle will be deeply covered with a coating of coal dust, which adheres so strongly to the agate surface that it is removed with difficulty. With other coals there will be only a thin film of coal dust adhering to the mortar and pestle, while with still others both mortar and pestle will be nearly as clean after the coal is pulverized as they were before the operation began. . . . The degree of adhesion seems to coincide with the coking qualities of the coal. If it adheres strongly the coal will probably make excellent coke; if it adheres only slightly the coal possesses the coking qualities to only a slight extent, if at all; and if the mortar shows no coating of dust the coal is to be regarded as noncoking. (PISHEL, M. A.: A Practical Test for Coking Coals. *Econ. Geol.*, vol. 3, pp. 265–275, 1908).

[2] Commonly the great calorie is used and spoken of as the calorie. It is the amount of heat necessary to raise the temperature of a Kilogram of water 1°C.

Ordinarily, to ascertain the heat value of coal the results are figured as if one Kilogram is burned. The heat value of the coal is the number of Kilograms of water that may be raised 1°C. If a pound of the same coal is burned and the B.T.U. ascertained then the B.T.U. should be 1.8 as much as the calories obtained. In actual heat units one B.T.U. equals $\frac{1}{3.968}$ Kilogram calories.

[3] GROUT, F. F.: The Composition of Coals. *Econ. Geol.*, vol. 2, pp. 225–241, 1907.

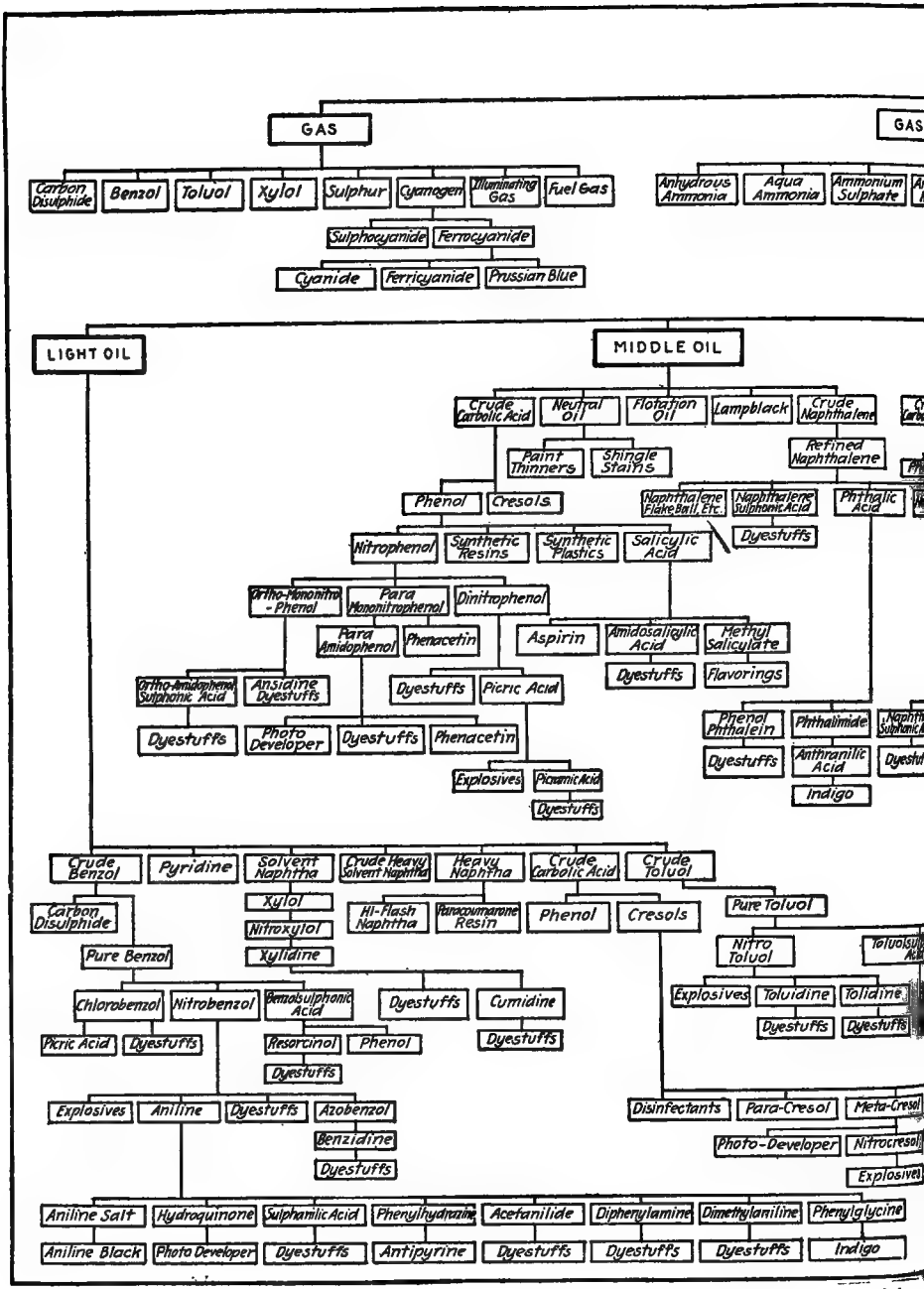
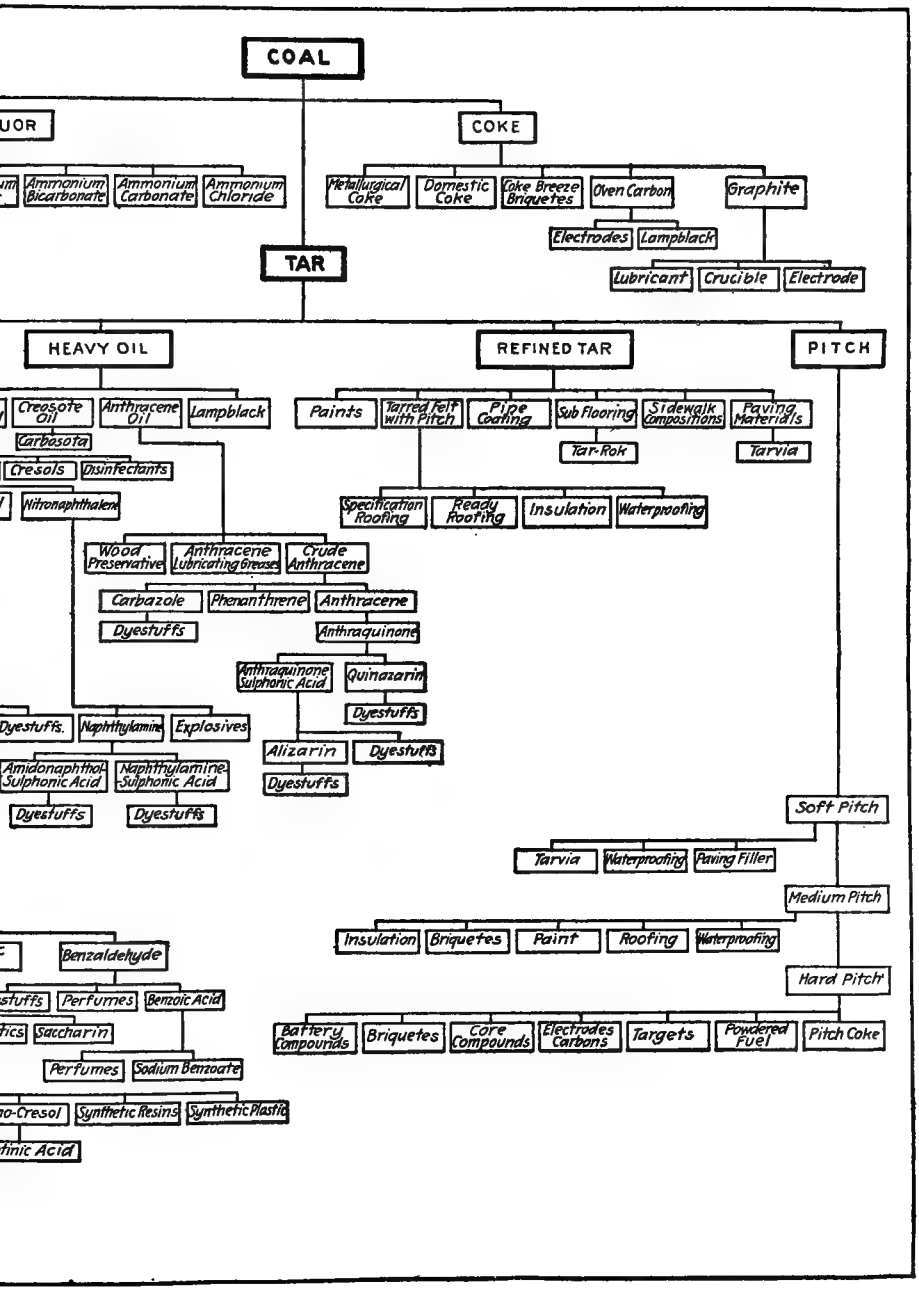


FIG. 17.—Diagram showing products derived from



. **(Based on data from the Barrett Company.)**

(Facing p. 30)

	Percentage of Fixed Carbon	Fuel Ratio, Carbon / Vol. Hydrocarbons
Graphite	99 to 100	99
Anthracite	93 to 99	13.28 to 99
Semianthracite coal	83 to 93	4.88 to 13.28
Semibituminous coal	73 to 83	2.70 to 4.88
Bituminous coal[1]	48 to 73	0.92 to 2.70
Cannel coal	35 to 48	0.53 to 0.92

There is much difference of opinion concerning the classification of subbituminous coal and lignite, and the physical properties of the coal enter into the classification to so large an extent that exact limits can not be set.

Structure and Texture of Coals.—The woody fiber seen in lignites is called *lignitoid*. The nuts, seeds, and bark found in

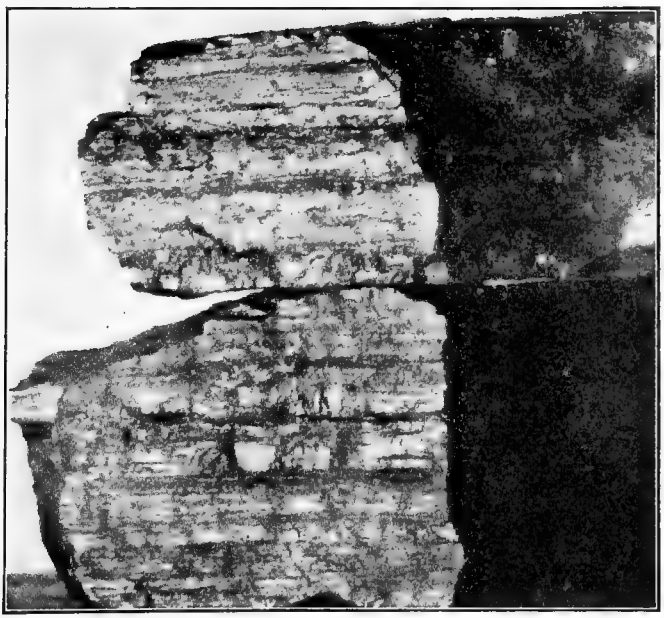


Fig. 18.—Piece of coal from Shelbyville, Illinois, about natural size. Shows striation and dark woody laminæ. (*After White and Thiessen.*)

many coals have already been mentioned. Microscopic study reveals the presence of plant spores and in some coals the remains

[1] Some coals classed as subbituminous on account of their physical character have fuel ratios as high as 1.69. And other coals classed as bituminous have fuel ratios as low as 0.84.

of bacteria and algal cells. Resinous bodies are common (Figs. 18–19). Some cannel coals are made up principally of spores.

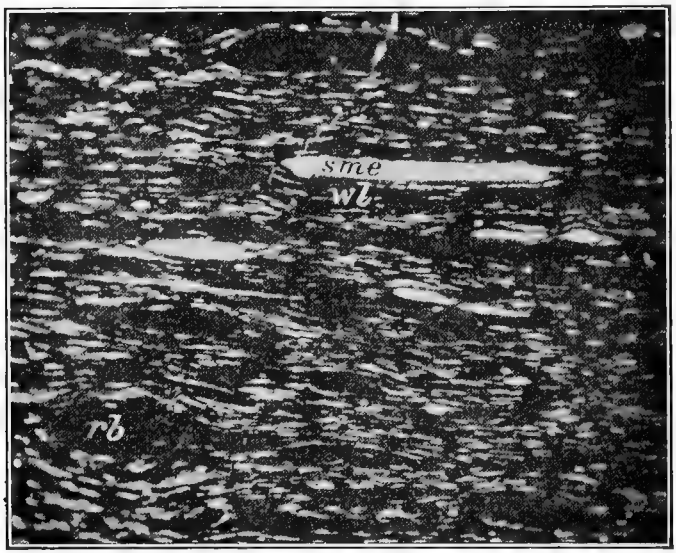


FIG. 19.—Section of coal, Fig. 18, across the bedding, magnified 50 times. The larger white patches (*sme*) represent small megaspore exines measuring between 0.5 and 1.0 mm. The small white patches are microspore exines. *wl*, woody laminæ; *rb*, resinous body. (*After White and Thiessen.*)



FIG. 20.—Forest wood superficially charred. (*After Grout.*)

and the material composed of spores is called *canneloid*. Some coals contain dense, black, spongy material[1] known as "mother

[1] GROUT, F. F.: The Relation of Texture to Composition of Coal. *Econ. Geol.* vol. 6, pp. 449–464. JEFFREY, E. C.: On the Composition and Qualities of Coal. *Econ. Geol.* vol. 9, pp. 730–742, 1914. WHITE, DAVID and THIESSEN, R.: The Origin of Coal. U. S. Bureau Mines *Bull.* 38, 1909.

of coal" or mineral charcoal (Figs. 20, 21). This material is generally supposed to represent burnt wood or charcoal buried in the bed at the time of its formation. As a rule the materials forming the coal are oriented with their long dimensions parallel to the bedding. In cannel coal, the higher grades of bituminous

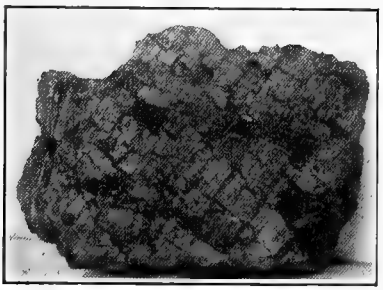


FIG. 21.—Mineral Charcoal. (*After Grout.*)

coal, and anthracite there is no decided tendency for the coal to break along the bedding. The cannels and the anthracite break with conchoidal fracture. The block coals break to form rectangular faces, and the better grades of bituminous coal break with a well-defined columnar cleavage (Fig. 4*b*, p. 12).

CHAPTER III

COAL FIELDS OF NORTH AMERICA

North America contains more coal than any other continent. The United States, Canada, and Alaska are well supplied. Mexico possesses several coal fields. One of these the Sabinos field across the Rio Grande from Eagle Pass, Texas, is known to be of great value. Central America contains little coal.

The greatest coal fields of the United States are situated in the Appalachian Plateau, in the interior plains, and in the Rocky Mountains (see Fig. 22). They are thus conveniently located with respect to centers of population. There are fields also in eastern Virginia and in western Washington, which, though smaller than the fields of the interior, are nevertheless valuable.

The coals of the United States are found in formations of Carboniferous, Triassic, Cretaceous, and Tertiary ages.

The Carboniferous, which is the principal coal-producing system in both the United States and Europe, is extensively developed in the eastern half of the United States. Three great subdivisions are recognized, namely the Mississippian ("Lower Carboniferous"), the Pennsylvanian ("Coal Measures"), and the Permian. Each subdivision carries coal. The Mississippian series, in a belt lying approximately along the border of Virginia and West Virginia, contains beds of anthracite in the Pocono formation. The beds are closely folded, locally overturned, and too impure to be mined except locally.[1] The chief coal-bearing subdivision of the Carboniferous is the Pennsylvanian. The Permian carries coal beds in Pennsylvania and in West Virginia, some of which are mined.

The Pennsylvanian extends over wide areas. It contains coal in North America at many places—Newfoundland; Nova Scotia; New Brunswick; Rhode Island and Massachusetts; the anthracite region of eastern Pennsylvania; the bituminous coal region of the Appalachians, extending from Pennsylvania to Alabama and

[1] White, I. C.: "Coal Report." W. V. Geol. Survey, vol. 2, pp. 1–9, 1908.

embracing parts of nine States; southern Michigan; southern Illinois, western Indiana and central western Kentucky; parts of

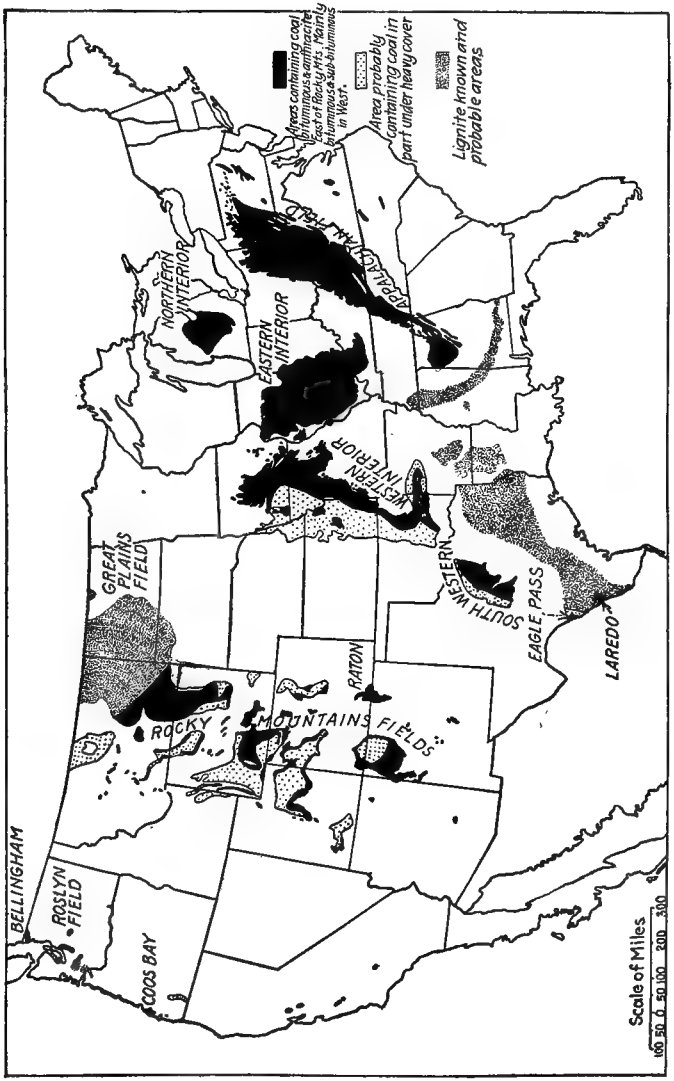


FIG. 22.—Sketch showing coal fields of the United States. (*After Campbell, Parker and others.*)

Missouri, Iowa, Kansas, Oklahoma and Arkansas; and northern Texas. Eighteen States of the Union contain important areas of workable Pennsylvanian coal.

All these areas are in structural basins, except the western interior area, most of which lies on the flanks of the Ozark dome and the Arbuckle-Ouachita uplift. In Kansas and Oklahoma the coal-bearing rocks dip westward below the great plain where they are covered by Permian and later rocks. Where the Pennsylvanian rises again near the Rocky Mountain region it is barren of coal except in a small area in northeastern New Mexico, where a 20-inch bed of bituminous coal is found in Pennsylvanian rocks in the upper Pecos Valley.[1]

In the north Texas field the coal measures lie between the Llano uplift and the Arbuckle Mountains. The beds dip west.

In the Triassic system near Richmond, Va., and in North Carolina, bituminous coal is found in two small basins. These coals were the first to be worked in the United States, but they are of slight extent and can not compete on equal terms with the better coals of the Appalachian fields.

In the West workable coal is found in both Mesozoic and Tertiary rocks. Large amounts are present in the Cretaceous and in the Eocene. At many places the coals occupy intermontane basins, some of which are very large, while others are small. There are several Tertiary coal fields in the Pacific Coast States, but all are small except some in Washington, which state contains several fields of considerable extent.

The coals of the Appalachian fields are in general better and contain less ash and moisture than any other coals in the United States. This is shown by the table of analysis on pages 20 and 21. The coals of the Western fields are generally lower grade, and the fields contain much lignite and subbituminous coal.

Pennsylvania Anthracite Region.—The anthracite field[2] in eastern Pennsylvania contains several long, narrow synclinal basins that trend northeast. These resemble the other synclinal basins of the Appalachian belt but are sufficiently deep to have preserved the coal measures, which generally have been eroded in the sharply folded belt. The productive area contains 484 square miles; a large part of the coal available has been mined.

[1] Gardner, J. H.: Isolated Coal Fields in Santa Fe and San Miguel Counties, New Mexico. U. S. Geol. Survey *Bull.* 381, pp. 447–451, 1895.

[2] Smith, A. D. W.: The Anthracite Region. Sum. Final. Rept. Geol. Survey Pennsylvania Vol. 3, pt. 1, pp. 1916–2152, 1895.

Stoek, H. H.: The Pennsylvania Anthracite Coal Field. U. S. Geol. Survey *Twenty-second Ann. Rept.*, part 3, pp. 55–177, 1900–1901.

The coal-bearing areas are shown in Fig. 23 and sections in Fig. 24. The coal beds are found in the Pottsville and Alle-

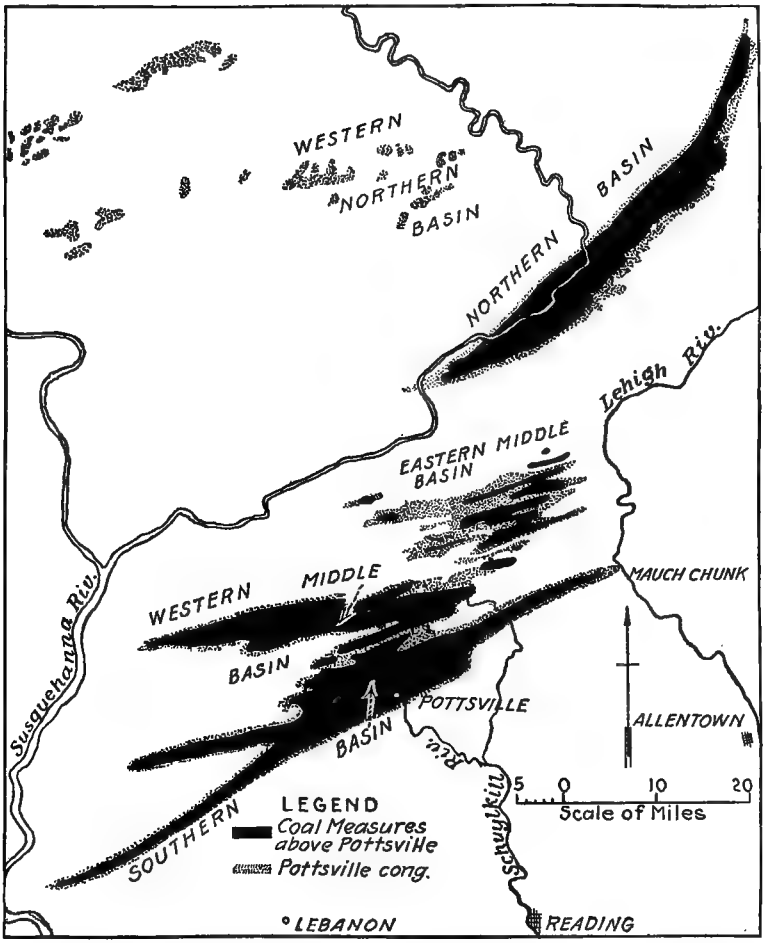


FIG. 23.—Sketch showing position of Pennsylvania anthracite area. The solid black shows the outlines of the main coal basins and the stippling represents the Pottsville formation. It contains some coal but lies below the main coal bearing formations. (*After Smith, Stoek and others.*)

gheny formations[1] which are closely folded. The maximum thicknesses of the portions of the coal measures remaining are

[1] WHITE, DAVID: The Stratigraphic Succession of the Fossil Floras of the Pottsville Formation in the Southern Anthracite Coal Field, Pennsylvania. U. S. Geol. Survey *Twentieth Ann. Rept.*, part 2, pp. 749–930, 1900.

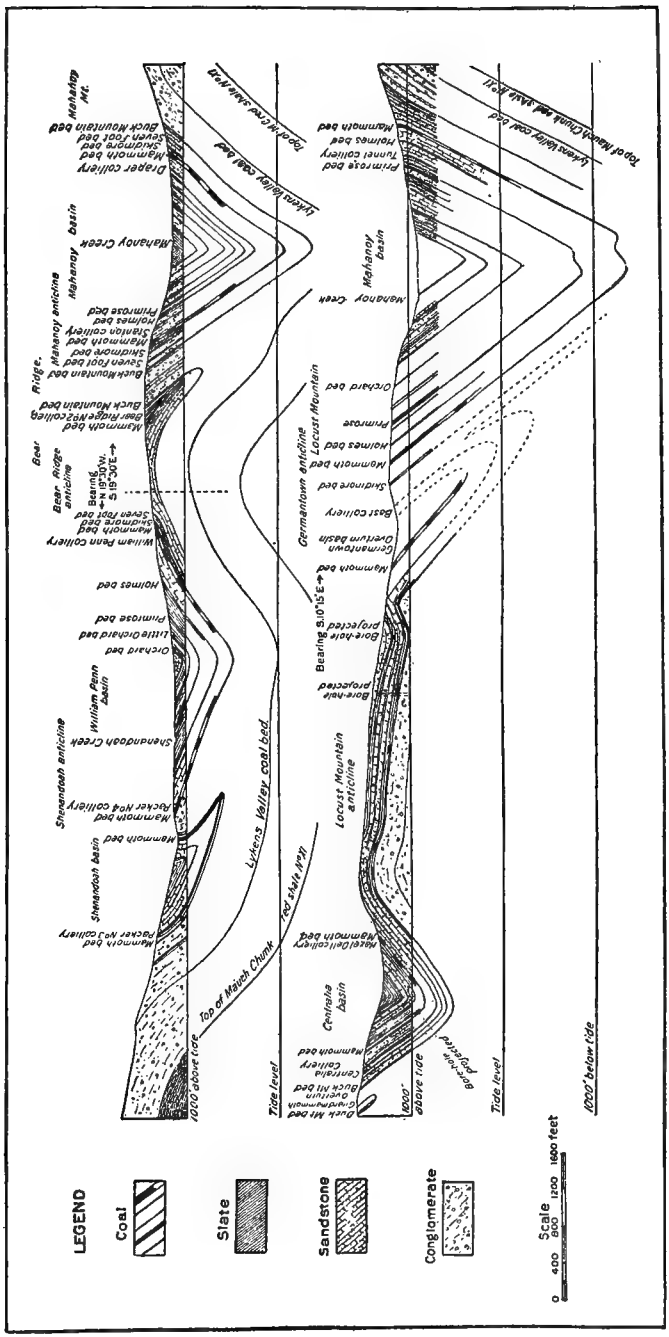


FIG. 24.—Sections of western-middle anthracite basin, Pennsylvania. The sections strike a few degrees east of south across the strike of the coal beds. (*After Smith, Stoek and others.*)

as follows: Northern field, 1,800 feet; eastern middle, 700 feet; western middle, 1,000 feet; southern, 2,500 feet.

The Coal Measures contain coal beds distributed throughout their whole extent, and the beds range in thickness from mere traces of coal to the Mammoth bed, which is 50 to 60 feet thick over wide areas. In general the lower 300 to 500 feet of the coal measures up to the top of the Mammoth bed contain the thicker deposits. These coal beds are separated by intervals ranging from a few feet to several hundred feet, but a barren interval of over 200 feet is rare. The rocks between the coal beds are sandstones merging into conglomerates, shales, and fire clays. The intervals between the same coal beds vary greatly in different basins and also in different parts of the same basin.

The coal is crushed, cleaned, and sized in great "breakers." It is widely distributed and is greatly prized as a domestic fuel. Analyses of Pennsylvania anthracites are stated on page 20.

ESTIMATED ORIGINAL TONNAGE OF COAL IN EASTERN AND INTERIOR COAL FIELDS, IN MILLIONS OF METRIC TONS (AFTER M. R. CAMPBELL[1])

Pennsylvania anthracite[2]	19,056
Pennsylvania bituminous[3]	102,154
Ohio	85,270
West Virginia bituminous[3]	138,425
Kentucky	111,913
North Carolina	181
Virginia bituminous[3]	20,417
Tennessee	23,289
Georgia	847
Alabama	61,328
Michigan	10,889
Indiana	48,141
Illinois	182,758
Iowa	26,461
Missouri[4]	76,225
Kansas	27,223
Oklahoma	49,865
Arkansas[5]	13,040

[1] CAMPBELL, M. R.: "Coal Resources of the World," vol. 2, p. 535. Toronto, 1913. The coal is bituminous unless otherwise stated.

[2] Includes also semianthracite.

[3] Includes also semibituminous coal.

[4] This estimate is by Hinds, see p. 64.

[5] Includes also semibituminous coal and semianthracite.

COAL PRODUCED IN THE UNITED STATES IN 1918

State	Total quantity (short tons)	Total value	Average value per ton
Alabama	19,184,962	$54,752,329	$2.85
Alaska	75,606	411,850	5.45
Arkansas	2,227,369	8,172,376	3.67
California and Idaho	6,400	17,250	2.70
Colorado	12,407,571	33,404,743	2.69
Georgia	66,716	239,377	3.59
Illinois	89,291,105	206,860,291	2.32
Indiana	30,678,634	70,384,601	2.29
Iowa	8,192,195	24,703,237	3.02
Kansas	7,561,947	22,028,142	2.91
Kentucky	31,612,617	80,666,842	2.55
Maryland	4,497,297	12,466,189	2.77
Michigan	1,464,818	5,615,097	3.83
Missouri	5,667,730	17,126,498	3.02
Montana	4,532,505	11,444,875	2.53
New Mexico	4,023,239	10,787,082	2.68
North Carolina	1,420	6,745	4.75
North Dakota	719,733	1,629,668	2.26
Ohio	45,812,943	118,095,518	2.58
Oklahoma	4,813,447	17,508,884	3.64
Oregon	13,328	37,454	2.81
Pennsylvania (bituminous)	178,550,741	463,159,736	2.59
South Dakota	7,942	22,230	2.80
Tennessee	6,831,048	19,305,203	2.83
Texas	2,261,135	5,937,997	2.63
Utah	5,136,825	13,937,097	2.71
Virginia	10,289,808	25,865,895	2.51
Washington	4,082,212	14,132,869	3.46
West Virginia	89,935,839	230,508,846	2.56
Wyoming	9,438,688	22,581,019	2.39
Total bituminous	579,385,820	$1,491,809,940	$2.58
Pennsylvania anthracite	98,826,084	336,480,347	3.40
Grand total	678,211,904	$1,828,290,287	$2.70

Appalachian Bituminous Coal Fields.[1]—The Appalachian coal field (Figs. 25, 26) extends from the northern border of Pennsylvania southwestward to central Alabama, a distance of 800 miles. Its greatest width is about 180 miles, near its north end, from which it tapers gradually southward to about 20 miles in Tennessee and then expands to about 80 miles in Alabama. It embraces portions of nine States and has a total



FIG. 25.—Outline map showing position of Appalachian bituminous coal fields.

estimated area of 70,000 square miles. It is by far the most important of the bituminous coal fields of the United States in extent, quality of coal, number and thickness of workable beds, state of development, and accessibility of great markets.

The coal-bearing formations (Carboniferous) consist for the

[1] WHITE, DAVID, CAMPBELL, M. R., and HASELTINE, R. M.: The Northern Appalachian Coal Field. U. S. Geol. Survey *Twenty-second Ann. Rept.*, part 3, pp. 125–226, 1900–1901.

WHITE, DAVID, and CAMPBELL, M. R.: The Bituminous Coal Field of Pennsylvania. *Idem*, pp. 127–200.

most part of shales, sandstones, and conglomerates, with occasional beds of limestone, fire clay, and coal. In general the formations show a gradual thinning from the eastern margin of the field westward, and there is also a decrease in the number and thickness of the coal beds toward the west.

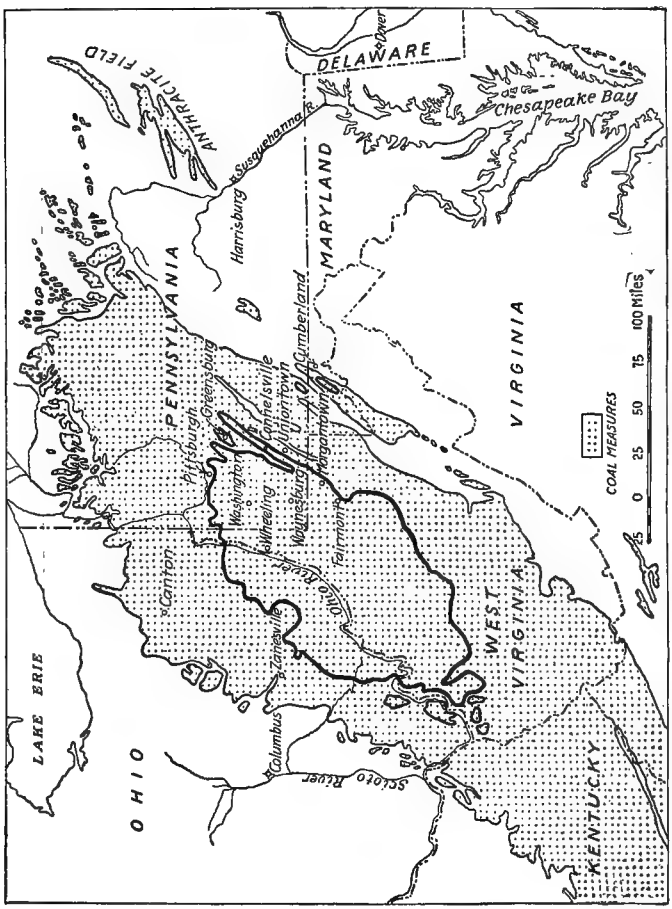


FIG. 26.—Sketch showing northern part of Appalachian coal field. Dotted area is the coal measures. The heavy black line divides the upper and lower measures. It is also the horizon of the Pittsburgh coal.

Pennsylvania.—In Pennsylvania the Pottsville series (Fig. 27) carries commercial coals of the Sharon and the Mercer group. The Sharon coal lies above a bed of shale and fire clay that rests on the Sharon conglomerate. It is a block coal highly prized as a domestic fuel and for blacksmithing. It is generally only 2 or 3 feet thick or less, although locally it reaches a thickness of 6 feet

of good coal. The Mercer contains two or more coals which are extensively mined in the northeastern part of the Appalachian basin. In general they are from 2 to 5 feet thick.

The Allegheny (Fig. 28) is an important coal-bearing series in Pennsylvania. Its lowest coal, the Brookville, is commonly too shaly and too sulphurous except for local use. The Clarion,

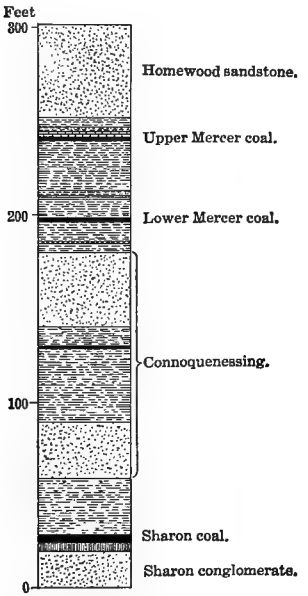


FIG. 27.—Section of the Pottsville formation in Mercer County, Pennsylvania. (*After I. C. White.*)

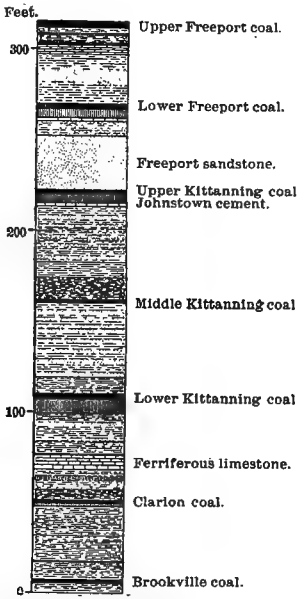


FIG. 28.—Section of the Allegheny formation on Allegheny River, Armstrong County, Pennsylvania. (*After White and Campbell.*)

which is 4 feet thick in Clarion County, is also impure and is mined only locally.

PRINCIPAL SUBDIVISIONS OF THE CARBONIFEROUS IN PENNSYLVANIA

	PRESENT NAME	OLD NAME
Permian	Dunkard formation or series	Upper Barren Coal Measures
Pennsylvanian	4. Monongahela	Upper Productive Coal Measures
	3. Conemaugh	Lower Barren Coal Measures
	2. Allegheny	Lower Productive Coal Measures
	1. Pottsville	Pottsville
Mississippian		

The Lower Kittanning is the most persistent coal of the Allegheny formation, although it seldom exceeds a workable thickness of 4 feet. Its purity, regularity, and accessibility make it first in production among the Allegheny coals.[1]

The Middle Kittanning is generally too thin for mining, and it is the poorest coal of the Kittanning group. It is about 2 feet thick in the Fifth basin, in Elk County. In Center County it reaches a thickness of 4 feet, but it is shaly.

In the value of its product the Upper Kittanning is fourth in importance of the Allegheny coals. It is remarkable for the variety of its composition and its patchy mode of occurrence. It contains most of the cannel shale, or so-called cannel coal, yet the areas of this cannel shale are very small and isolated. The cannel shale and thin coals southeast of New Bethlehem have been mined to some extent and hauled by wagon for shipment to gas factories.

The Lower Freeport coal is, next to the Lower Kittanning, the most valuable of the coals of the Allegheny formation in Pennsylvania.[1]

The Upper Freeport,[1] the highest of the Allegheny coals, lies just beneath the Mahoning sandstone, the lowest member of the Conemaugh formation. It is a variable and complex bed that extends over a great area, although in a considerable portion of this area it is too much broken up and too impure for profitable mining. It is the Lemon coking seam along the Allegheny front, in eastern Cambria County, where it thins and becomes shaly in passing southward to the Maryland line.

The division of the Coal Measures next overlying the Allegheny formation in Pennsylvania is the Conemaugh formation (Fig. 29), more commonly known as the "Lower Barren Measures." It lies between the Upper Freeport coal, the topmost bed of the Allegheny formation, and the floor of the Pittsburgh coal, the basal stratum of the Monongahela formation.

The coals of the Conemaugh formation are variable in thickness. Several of the seams are persistent over large areas, but they are extremely irregular. Most of those that are thick enough for mining contain so large a proportion of earthy material as to unfit them for commercial exploitation. Coal of the Conemaugh is mined in the Berlin basin.

[1] For analyses see page 20.

The Monongahela (Fig. 30) or upper productive formation extends from the bottom of the Pittsburgh coal to the top of the Waynesburg coal, and has an average thickness of about 360 feet. The series is confined to the southwest corner of the State, where it occupies all or parts of seven counties.

Aside from the great Pittsburgh bed, which forms the base, the series contain a number of coals that are locally workable.

The Pittsburgh coal is the most

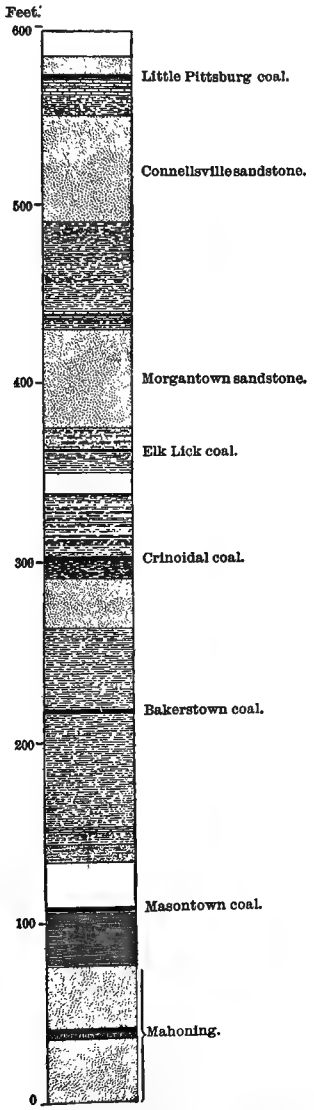


FIG. 29.—Section of the Conemaugh formation on Dunbar Creek, Fayette County, Pennsylvania. (*After I. C. White.*)

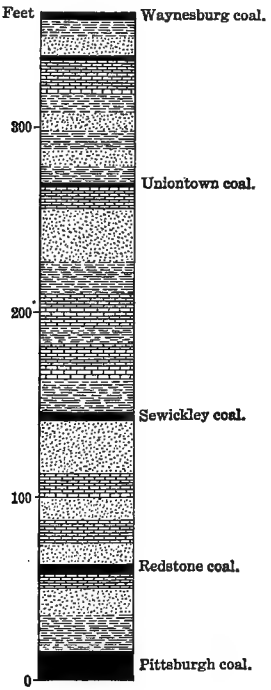


FIG. 30.—Section of the Monongahela formation in Fayette County, Pennsylvania. (*After Stevenson.*)

uniform in quality and thickness and, for a given area, the

most valuable coal bed in the bituminous coal field of Pennsylvania. As it occurs at the base of the Monongahela formation, it coincides in extent with that formation in Pennsylvania, as shown on Fig. 26. It occupies an area in this State about 50 miles in length by 50 miles in breadth, and its average thickness is about 6 feet. It is estimated that the Pittsburgh coal bed originally contained more than 10,000,000,000 tons of available coal.

In quality the coal of the Pittsburgh bed is for many purposes perhaps equal if not superior to the best bituminous coal found elsewhere in the Appalachian field or in the world.[1] It is an excellent domestic and steam fuel, and its calorific value is high.

A great area of Pittsburgh coal occupies the synclinal trough west of Chestnut Ridge. This is the well-known Connellsville basin, famous for coke made of the Pittsburgh coal. This basin is about 60 miles long and from 2 to 6 miles wide (Fig. 6).

Throughout the basin the coal bed consists of two divisions, separated by a clay parting from 6 to 12 inches thick. The roof division ranges from a few inches to 5 feet in thickness, but the coal in this part is interstratified with shale bands, and it is generally regarded as worthless. The lower bench is from 7 to 9 feet thick. In some localities it is free from shale, but generally there is a thin shale about 18 inches from the floor, and a few other shale partings come in irregularly.

The coal is soft, breaks readily and is easily mined. The composition of standard Connellsville coal, is shown by analysis 10, page 20.

The coke from the Connellsville region has a silvery luster, a cellular structure, and a sharp metallic ring. It is tenacious, comparatively free from impurities, and capable of bearing a heavy burden in the blast furnace. It is low in phosphorus.

The Greensburg basin lies west of the north end or the Connellsville basin. It has a width of about 3 miles in its widest part and a length of 12 miles, extending from a point a little southwest of Greensburg northeastward nearly to Conemaugh River. The roof division of the coal is from 4 inches to 3 feet thick and has no commercial value. The main bench of coal is from 6 to 8 feet thick.

The Redstone coal bed occurs from 40 to 60 feet above the Pittsburgh coal, and, owing to this close proximity, it perhaps can

[1] For analyses see p. 20.

not be worked after the removal of the great bed so close below it. In its best development it ranges from 3 to 4 feet in thickness, but over much of the territory it is thinner.

The Sewickley coal lies about 130 feet above the Pittsburgh coal. It is widely persistent, but it is economically valuable over a comparatively small area. Its best development is found along Monongahela River in Greene County, where it is from 5 to 6 feet thick, with 2 to 3 inches of shale near the middle of the bed. It is much prized as a domestic fuel.

The Uniontown coal is 3 feet thick and is mined in Fayette and Washington counties. The Waynesburg coal, at the top of the Monongahela series, is much broken by shale partings, but is mined.

The Dunkard formation (Fig. 31) contains several coals, although they are all either thin or much broken by shale partings.

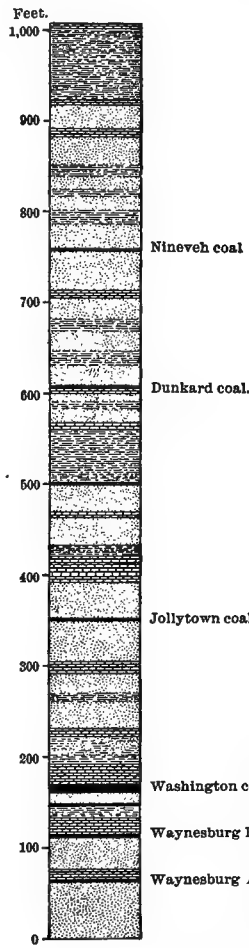


FIG. 31.—Section of the Dunkard (Permian) formation in Greene County, Pennsylvania. (*After Stevenson.*)

Ohio.—The coal fields of Ohio[1] lie in the eastern part of the State, extending from near the shore of Lake Erie in Geauga and Lake counties southwestward to Scioto and Lawrence counties, on Ohio River. An area of about 12,600 square miles, nearly one-third of the State, is underlain by coal-bearing rocks.

The Ohio fields contain eleven coal beds that are regularly mined for railroad shipment. These beds, named and numbered from the bottom up, are the Sharon (No. 1), Quakertown (No. 2), Upper Mercer (No. 3*a*), Clarion (No. 4*a*),

[1] BOWNOCKER, J. A.: The Coal Field of Ohio. U. S. Geol. Survey *Prof. Paper*, 100-B, pp. 35–95, 1917.

Lower Kittanning (No. 5), Middle Kittanning (No. 6), Upper Freeport (No. 7), Mahoning (No. 7*a*), Pittsburgh (No. 8), Pomeroy (No. 8*a*), and Meigs Creek (No. 9). Two other beds, the Brookville (No. 4) and Lower Freeport (No. 6*a*), are regularly mined at some places to supply local demand, and eight others are occasionally mined at favorable places.

The coal-bearing Rocks of Ohio are part of the great structural trough of the Appalachians. The deepest part of this trough is in West Virginia along a line running almost direct from Pittsburgh, Pa., to Huntington, W. Va. Toward this deepest part the rocks dip on both sides, those in Ohio dipping generally southeastward 1 degree or less. All the Ohio coals are bituminous.

The Allegheny formation, formerly known as the "Lower Productive Coal Measures," contains the most extensive and valuable coal beds of Ohio. It extends in outcrop from Mahoning to Lawrence County and has a thickness of 250 feet. The Brookville (No. 4) coal is the lowest member of the formation, and the Upper Freeport (No. 7) coal is the highest. The formation contains five coal beds that are mined in a large way, and one of these is of workable thickness above drainage level in every county where it is due.

SECTION OF THE ALLEGHENY FORMATION AT MAGNOLIA, IN SOUTHERN STARK COUNTY, OHIO

By Edward Orton

	FEET	INCHES
Coal, Upper Freeport (No. 7)	2	0
Clay, shale, sandstone, and concealed[1]	45	0
Sandstone, Lower Freeport,[1] and conglomerate	30	0
Concealed	55	0
Coal, Middle Kittanning (No. 6)	3	0
Clay	3	0
Shale	15	0
Coal	1	6
Shale	1	10
Coal, Lower Kittanning (No. 5)	3	6
Clay	3	0
Shale and sandstone	5	2
Limestone, Putnam Hill	1	8
Coal, Brookville (No. 4)	5	0
	174	8

[1] The Lower Freeport (No. 6*a*) coal does not appear in this section. It probably lies in the "concealed" mass above the Freeport sandstone member.

GENERALIZED SECTION OF THE MONONGAHELA FORMATION IN BELMONT AND ADJOINING COUNTIES, OHIO

By D. D. Condit

	Feet
Coal, Waynesburg, mined at Somerton, Newcastle, and Hunter, Belmont County; high in ash; usually a solid bed with no persistent clay or bone bands.	
Clay and sandy shale	18
Coal, thin.	
Clay and buff limestone	4
Sandstone, varying from shaly and cross-bedded to massive; quarried west of Miltonsburg, Monroe County	50
Coal, Uniontown; mined near Hunter, Belmont County, and along Sunfish Creek, east of Woodsfield, Monroe County; high in ash and usually has several clay bands.	
Clay, with thin layers of nodular limestone	10
Sandstone, shaly	18
Limestone (Benwood member), numerous beds 1 to 2 feet thick, interlayered with calcareous clay. In the lower portion is a conspicuous bed of olive-green clay	72
Coal, Meigs Creek; workable in Belmont County and also over much of Noble, Washington, and other counties to the southwest; rather high in ash but seldom has persistent bands of clay or bony coal.	
Sandstone, varying from shaly to massive and coarse grained	35
Coal, Lower Meigs Creek; workable in a few localities near Temperanceville, Belmont County, and southward in Monroe County; contains many bands of impurities and much "sulphur."	
Limestone	4
Shale and clay	25
Limestone, yellowish	3
Sandstone, shaly	30
Coal, Pomeroy; thin or wanting	
Limestone, laminated, black, underlain by yellowish limestone layers	4
Shale, sandy	20
Coal, Pittsburgh; present in workable thickness throughout nearly the whole of Belmont County and parts of the surrounding counties.	
	293

The Middle Kittanning (No. 6) coal (Fig. 32), on account of its quantity and quality, is the most valuable in Ohio.[1] It is found along the State line in Columbiana County and can be followed across the State to Lawrence County on Ohio River. It is workable in every county where it appears above drainage level, and in most of them on a large scale. The bed lies 20 to 35 feet above the Lower Kittanning coal.

The Pittsburgh or No. 8 coal is one of the two most valuable

[1] For analyses see p. 20.

coal beds in Ohio, its only rival being the Middle Kittanning (No. 6) bed, which is more persistent, has a larger acreage, and is of a little better quality. The Pittsburgh coal in Ohio occupies three widely separated fields—the Belmont County field, the Federal Creek field of Morgan and Athens counties, and the Swan Creek field of Gallia County. Outside of these fields the coal is thin and usually worthless.

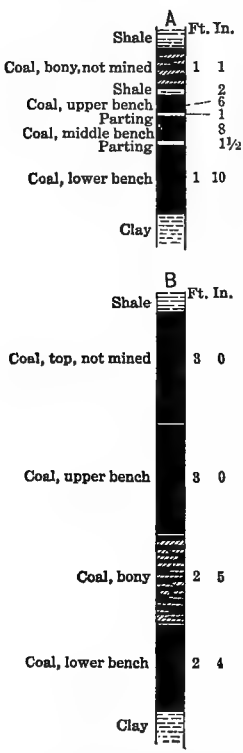


FIG. 32.—Sections of Middle Kittanning (No. 6) coal bed in Perry County, Ohio. A, Harrison Township; B, Pike Township. (*After Bownocker.*)

Maryland.—The coals of Maryland[1] are found only in the western part of the State. They occupy a strip along the west border of Allegheny County, about 20 miles long and with an average width of 5 miles, and cover the greater part of Garrett County. They lie in three broad synclines that trend northeast. The area which is underlain by workable coal is only 455 square miles. Although the area is small, the quality of the coal produced is excellent.

The Maryland coal field is in the southern extension of the eastern part of the bituminous field of Pennsylvania. Coals are found in the Pottsville, Allegheny, Conemaugh, and Monongahela formations. The Elk Garden, or Pittsburgh coal (Big bed), at the base of the Monongahela, is the most productive. This coal bed is confined to the Potomac basin. It formerly supplied most of the Cumberland coal of commerce, well known for its high quality, but it is approaching exhaustion in Maryland.

Virginia.—The Carboniferous coal measures are found in the western part of Virginia, where they occupy an area of

[1] MARTIN, G. C., and ABBE, CLEVELAND, JR.: Garrett County. Md. Geol. Survey, pp. 1–340, 1902.

CLARK, W. B.: Origin, Distribution and Uses of Coal. Md. Geol. Survey, vol. 5, pp. 221–240, 1905.

WHITE, DAVID: The Bituminous Coal Field of Maryland. U. S. Geol. Survey *Twenty-second Ann. Rept.*, part 3, pp. 201–214, 1901.

1,550 square miles. The Pocahontas field, in Tazewell and Buchanan counties, is well known. In Tazewell County, the Pocahontas vein No. 3 is from 4 to 10 feet thick, the maximum at Pocahontas, where it was first opened. The coal is known as one of the best steam coals in the world.[1] It makes good coke and burns with little smoke. It is highly prized as a coal for steamships on account of its low ash. The coal-bearing area lies west of an area of great deformation (Fig. 33). The Pocahontas coal is in the Pocahontas formation of the Lower Pottsville series. At higher horizons are other coal beds of workable thickness and good grade.[2]

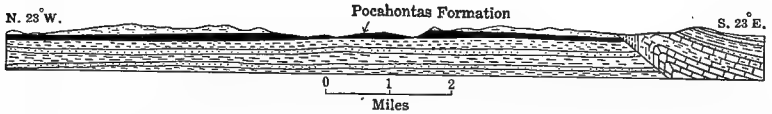


FIG. 33.—Cross-section showing structure of Pocahontas coal field 3 miles west of Pocahontas, Va. (*After M. R. Campbell and David White, U. S. Geol. Survey.*)

West Virginia.— The coal-bearing Pennsylvania rocks extend southward from Pennsylvania and Maryland into West Virginia, where they occupy a broad belt. The area underlain by workable coal in West Virginia is 17,000 square miles. The coals are bituminous and semibituminous coals of exceptionally good grade, and many of the beds are thick.

The coals of West Virginia are all of Carboniferous age. The oldest coals are in the Pocono formation of the lower Carboniferous, or Mississippian series. These coals are found along the boundary between Virginia and West Virginia and consist of thin beds of impure anthracite, probably not valuable except for local use. The beds dip at high angles and in places are overturned.[3]

The Pocahontas formation of Virginia extends westward into

[1] WATSON, T. L.: The Pocahontas or Flat Top Coal Field. *Mineral Resources of Virginia*, pp. 359–380, Jamestown Exposition, 1907.

[2] CAMPBELL, M. R.: U. S. Geol. Survey *Geol. Atlas.* Pocahontas folio (No. 26), 1896; Tazewell folio (No. 44), 1897; The Geology of the Big Stone Gap Coal Field, Virginia and Kentucky. U. S. Geol. Survey *Bull.* 111, pp. 1–106, 1893.

[3] WHITE, I. C.: "Coal Report," W. Va. Geol. Survey, vol. 2*a*, pp. 1–9, 1908.

eastern West Virginia,[1] where it contains six coal beds. Here, as in Virginia, the third Pocahontas seam is extensively developed. It is a smokeless coal with about 5 per cent. of ash and 0.6 per cent. of sulphur. At many places the Pocahontas N. 3 coal is from 5 to 7 feet thick, although it generally contains some thin shale partings. Much of the coal is semibituminous.[2]

Above the Pocahontas formation is the Middle Pottsville containing strata of the New River group[2] which include several beds of excellent coal. Some of the coal is equal to the Pocahontas in grade and is as low in ash. There are three coal beds, and two of them are workable at many places. They are about 4 to 6 feet thick. The New River and Pocahontas coals are so low in ash and so high in heat value that they are greatly in demand for use below naval boilers. Both have coking qualities. The presence of some ash in coke gives the coke strength to bear a burden in a furnace. The United States Steel Co. has fotund it practicable to ship low-ash New River coal to Sharon, Pa., to mix with other coal that is higher in ash for making furnace coke.

Above the New River is the Kanawha formation or Upper Pottsville. This formation also contains many beds of coal. The coals are higher in volatile matter than the New River coal. At least 10 beds are of workable thickness in places. Many of them are from 2 to 6 feet thick.

The Allegheny formation, which is well developed in Pennsylvania, extends into West Virginia. In the northern part of West Virginia it contains the Kittanning and Freeport coals, as in Pennsylvania (p. 43). In southwestern West Virginia it becomes thin and the coal beds thin or play out also, except those of the Kittanning horizon. The Davis or Roaring Creek coal of the Kittanning horizon is probably the only one of the Allegheny series that extends continuously across the State in valuable beds. It is 5 to 7 feet thick but at most places contains bone or shale partings. The Upper Freeport coal, which is valuable in Pennsylvania, begins to fail in the first tier of counties in northern West Virginia.

[1] These data are abstracted mainly from vols. 2, 2*a*, and other volumes of the W. Va. Geol. Survey, by I. C. White, R. V. Hennen, and G. P. Grimsley, and from a series of geologic folios, by M. R. Campbell and associates, covering an area which extends from Pocahontas, Va., through West Virginia to Ohio.—W. H. E.

[2] For analysis see p. 20.

The Conemaugh formation of the Pennsylvania series, which is represented in West Virginia by the upper part of the Charleston formation and the Braxton formation, contains the Bakerstown and Elk Lick coals and two other beds that are locally workable.

The Monongahela formation of Pennsylvania extends into western West Virginia. At its base is the Pittsburgh coal, which covers more than 1,000,000 acres in this State. In general the coal is 6 to 9 feet thick. White[1] found that the average of 95 widely spread samples of this coal gave: moisture 1 per cent., volatile matter 38.5 per cent., fixed carbon 53.5 per cent., ash 7 per cent., sulphur 2.5 per cent. Coals of the Monongahela formation above the Pittsburgh are the Redstone, Sewickley, Uniontown and Waynesburg.

The Dunkard formation (Permian) contains the Washington coal.

Eastern Kentucky.—Kentucky contains parts of two great Carboniferous coal fields. The Appalachian field extends into the eastern part of the State and the Eastern Interior field into the western part. Between these two great coal fields is the Cincinnati arch, on which older Paleozoic sedimentary rocks separate the two fields. The eastern Kentucky field is mainly in the great Appalachian Plateau which is deeply dissected by streams. The rocks dip southeast at low angles. In the southeastern part of the State the strata are disturbed by the great Pineville fault which separates the Jellico and Middleboro coal basins (see Fig. 25, p. 41). The coal, which is in the Pennsylvanian series is of good bituminous grade.[2]

In the Elkhorn coal field, southeastern Kentucky,[3] coal is mined from several beds. The Elswick coal, about 60 feet above the Lee conglomerate, is 30 inches thick. The Auxier bed, about 200 feet higher, is about 33 inches thick; above that is the Millard coal, 36 inches thick, and the Bingham coal, 30 to 53 inches thick. The lower Elkhorn, 750 feet above the Lee conglomerate, is 4 feet

[1] White, I. C.: *op. cit.*, vol. 2*a*, p. 645.

[2] Campbell, M. R.: U. S. Geol. Survey Geol. *Atlas*, Richmond folio (No. 46); London folio (No. 47); Estillville folio (No. 12).

Hodges, J. M.: Report on Coals of Macies and Leatherwood Creek, Perry County, Kentucky Geol. Survey *series* 4, vol. 1, part *F*, pp. 7–68, 1914.

[3] Stone, R. W.: The Elkhorn Coal Field, Kentucky. U. S. Geol. Survey *Bull.* 316, pp. 42–54, 1907.

thick and is badly broken by movements. The Upper Elkhorn, about 1,000 feet above the Lee conglomerate, is about 8 feet thick in places, and its average thickness in the Elkhorn field is over 5 feet. All these coals are high-grade bituminous coals, and many of them are low in ash. The low percentages of sulphur, phosphorus, and ash in the Upper Elkhorn coal renders it especially desirable for making metallurgical coke.

Southern Appalachian Coal Field.—The southern Appalachian coal field (Fig. 25, p. 41) coincides essentially with the Cumberland Plateau and outliers and includes parts of Kentucky, Tennessee, Alabama, and Georgia. Most if not all of the coal-bearing rocks correspond to the Pottsville group of Pennsylvania. On the basis of the structure the field is divided into three districts which have affected also the commercial development of the coal. These are the Jellico, Chattanooga, and Birmingham districts.[1]

The Jellico district includes the Middleboro, Jellico, and Wartburg basins. The Middleboro basin is a long, narrow, syncline which includes also the Bigstone Gap field in Virginia. The Middleboro basin contains several coal beds. The Bryson bed has been extensively mined; it is 250 feet above the Lee conglomerate and is probably the same as the Sewanee bed to the southwest. It is a high-grade bituminous coal about 4 feet thick and is nearly uniform in thickness and character over a large area.

The Jellico basin is northwest of the Middleboro basin and is separated from it by the Pineville fault. The coal beds are less numerous and thinner than in the Middleboro basin. The Jellico bed, which is mined, is 3 feet thick.[2] It is probably the same as the Sewanee or the Bryson bed of the Middleboro basin. Some other beds have been mined locally.

The Wartburg basin is south of the Jellico basin. A bed 4 feet thick, corresponding to the Sewanee bed, is mined here, as is also a bed higher up in the Wartburg sandstone. There are also other thick beds of excellent quality.

[1] Hayes, C. W.: The Southern Appalachian Coal Field. U. S. Geol. Survey *Twenty-second Ann. Rept.*, part 3, pp. 227–263, 1902.

Ashley, G. H. and Glenn, V. C.: Geology and Mineral Resources of a Part of the Cumberland Gap Coal Field, Kentucky. U. S. Geol. Survey *Prof. Paper*, 49, pp. 1–239, 1906.

[2] For analysis see p. 20.

The Chattanooga district[1] includes the territory from Emory River southward a short distance into northern Georgia and Alabama. It includes the Sewanee basin, which is a portion of the Cumberland Plateau, the Walden basin, separated from the Cumberland Plateau on the west by Sequatchie Valley, and the Lookout basin, which occupies the northern portion of the Lookout Mountain syncline.

The Walden basin is a long, narrow syncline. At places two beds are worked. The principal one is the Sewanee bed, which is generally 4 feet or more thick. The Sewanee basin is west of the Sequatchie Valley and extends southwestward about halfway across Tennessee. Much of the coal of this basin is in the Sewanee bed, which is famous for its persistence and thickness and for the quality of its coal.[2]

The Pennsylvanian rocks extend southwestward across the Tennessee boundary into Georgia and Alabama. Only a small area in north-

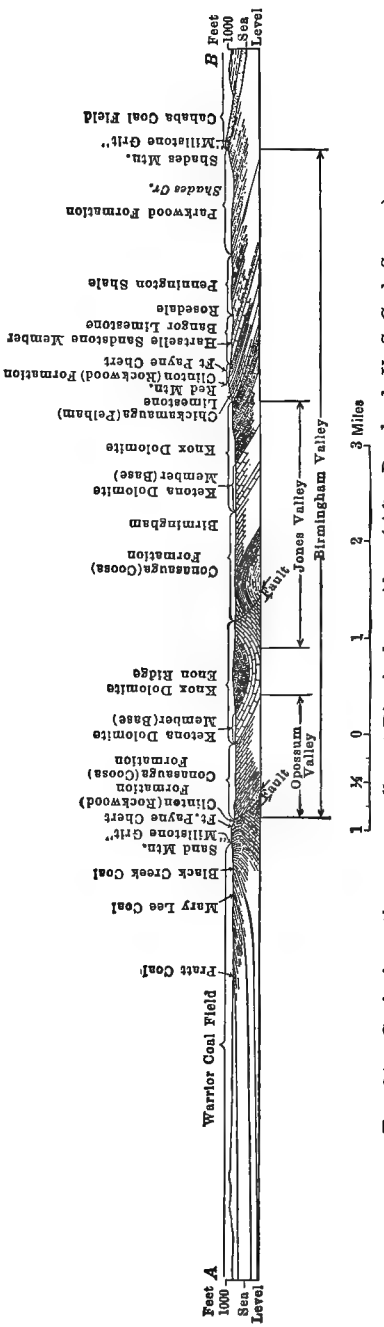


FIG. 34.—Geologic section across valley at Birmingham, Ala. (*After Burchard, U. S. Geol. Survey.*)

[1] GLENN, L. C.: The General Features of the Tennessee Coal Field North of the Tennessee Central Railroad. *Res. Tenn.*, vol. 6, No. 3, pp. 127–154. Tenn. Geol. Survey, 1916.

[2] For analysis see p. 20.

western Georgia is underlain by Pennsylvanian rocks, but the belt expands greatly toward the southwest and occupies a wide area in Alabama near Birmingham. The rocks are thrown into northeasterly folds and the coal measures lie in basins, chief of which is the Warrior basin.[1]

In the Warrior basin the coals are all of bituminous grade. They are used extensively for making coke to smelt iron ore. Most of the coke is made from coal of the Pratt and Mary Lee beds (Fig. 34). The coal beds are from 2 to 6 feet thick but generally contain one or more thin shale breaks. The coals average about 58 per cent. of fixed carbon, 27 per cent. of volatile hydrocarbons, 10 per cent. of ash, 2 per cent. of moisture, and 2 per cent. of sulphur. They are good fuel and steam coals, and their coking property gives them exceptional value. The coal as it comes from the mines contains clay and shale, which are removed by washing the slack and crushed coal in specially constructed washeries.

Northern Interior Coal Field.—The Northern Interior coal field lies in the structural basin of the Lower Peninsula of Michigan. The field embraces an area of about 7,500 square miles. The coal measures are equivalent to the Pottsville formation, in the lower part of the Pennsylvanian series, and in the center of the basin have a thickness of 600 to 700 feet. There are seven beds of workable coal, which are from 2 to 4 feet thick. As the lower coal beds in the center of the basin were probably laid down before the lower beds on the outer rim,[2] the basin was probably sinking during the deposition of the coal. Sections of the rocks are shown in Figs. 35 and 36. The coal is a bituminous coal of good grade[3] and ranks high for making steam. It is a coking coal but rather high in sulphur.

Eastern Interior Coal Field.—The Eastern Interior coal field covers most of Illinois, the southwest corner of Indiana, and a

[1] Butts, Charles: Iron Ores, Fuels, and Fluxes of the Birmingham District, Alabama. U. S. Geol. Survey *Bull.* 400, pp. 170–198, 1910.

Nelson, W. A.: The Tennessee Coal Field South of the Tennessee Central Railroad. *Res. Tenn.*, vol. 3, No. 1, pp. 26–49, Tenn. Geol. Survey, 1913.

[2] Lane, A. C.: The Northern Interior Coal Field. U. S. Geol. Survey *Twenty-second Ann. Rept.*, part 3, pp. 313–331, 1902.

[3] For analysis see p. 20.

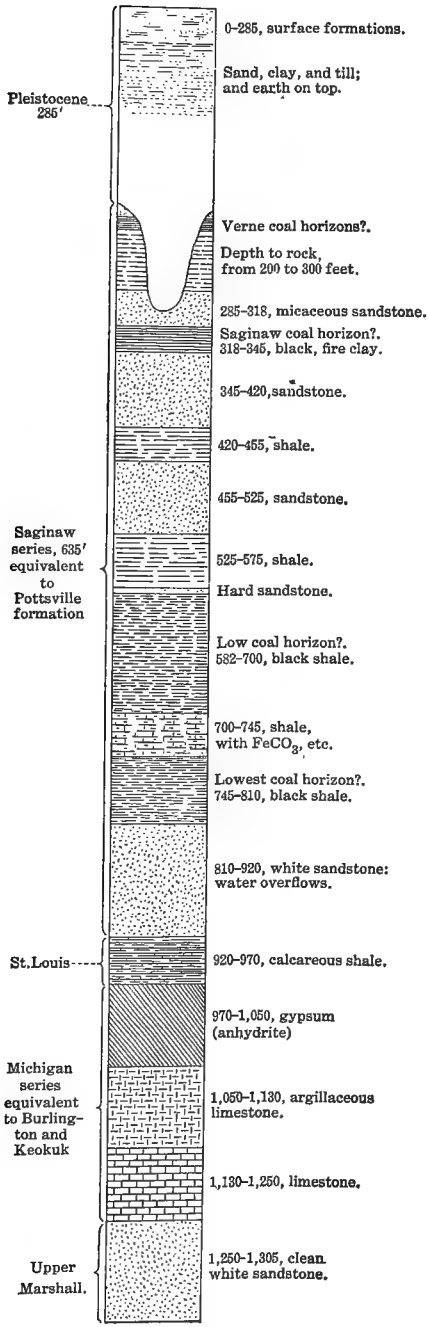


FIG. 35.—Section in well at Midland, Mich. (*After Lane.*)

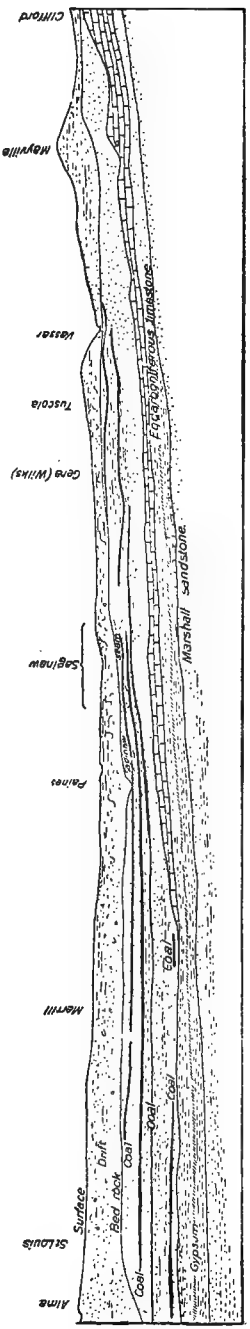


FIG. 36.—Section on line of Pere Marquette Railway from Alma eastward through Saginaw to Clifford, Mich. (*After Lane.*)

small part of western Kentucky.[1] The coal-bearing rocks are of Pennsylvanian age. The field was possibly once continuous with the Appalachian field but the coal-bearing rocks have been eroded from above the Cincinnati arch, which occupies western Ohio, eastern Indiana, and central Kentucky. The field covers 35,600 square miles in Illinois, 6,500 square miles in Indiana, and 4,900 square miles in Kentucky, or a total area of 47,000 square miles. Figure 37 is a map and Fig. 38 shows cross-sections of the area. The rocks dip from the edge of the area toward the center. Because the coals are nearer the surface at the outer rim than toward the center of the basin, the most highly developed area is around the rim.

The Pennsylvanian series rests on the older Paleozoic rocks. As a rule there is a sandstone member from a few feet to 200 feet thick. Above this is the Wabash group, from 100 to 600 feet thick, which constitutes the main coal-bearing measures. Above the Wabash is the Merom group, or "Upper Barren Measures," which has a maximum thickness of about 400 feet. At most places the surface is covered with drift.

In Indiana the coal-bearing rocks are subdivided into eight divisions, based on that number of main coals or coal horizons. The coal beds are regarded as forming the lower limits of the several divisions and bear the same numbers. Thus Coal VI marks the base of Division VI, minor coals in that division being designated Coals VI*a*, VI*b*, etc. In Illinois the coals have been designated from 1 to 15. In Kentucky the coals have been assigned numbers and letters, the numbers beginning at the bottom and running up to 12. Numbers 9, 11, and 12 are the principal

[1] Ashley, G. H.: The Eastern Interior Coal Field. U. S. Geol. Survey *Twenty-second Ann. Rept.*, part 3, pp. 271–305, 1902.

Bain, H. F., Parr, S. W., Grout, F. F., and others: Contributions to the Study of Coal. Ill. Geol. Survey *Bull.* 4, pp. 187–212, 1907.

Bain, H. F., DeWolf, F. W., Udden, J. A., and others: Contributions to the Study of Coal. Ill. Geol. Survey *Bull.* 8, pp. 151–172, 1908.

DeWolf, F. W., Bement, A., Savage, T. E., and Cady, G. H.: Studies of Illinois coal. Ill. Geol. Survey *Bull.* 16, pp. 177–301, 1910.

De Wolf F. W.: The Coal Resources of Illinois. Ill. Geol. Survey *Bull.* 14, pp. 189–196, 1909.

Lee, Wallace: Coal in Gillespie and Mount Olive Quadrangles. Ill. Geol. Survey *Bull* 30, pp. 51–59, 1917.

Parr, S. W.: The Chemical Composition of Illinois Coal. Ill. Geol. Survey *Bull.* 16, pp. 203–243, 1910.

coals worked. The letters begin at the top, coals A, B, and D corresponding to 12, 11, and 9 respectively.[1]

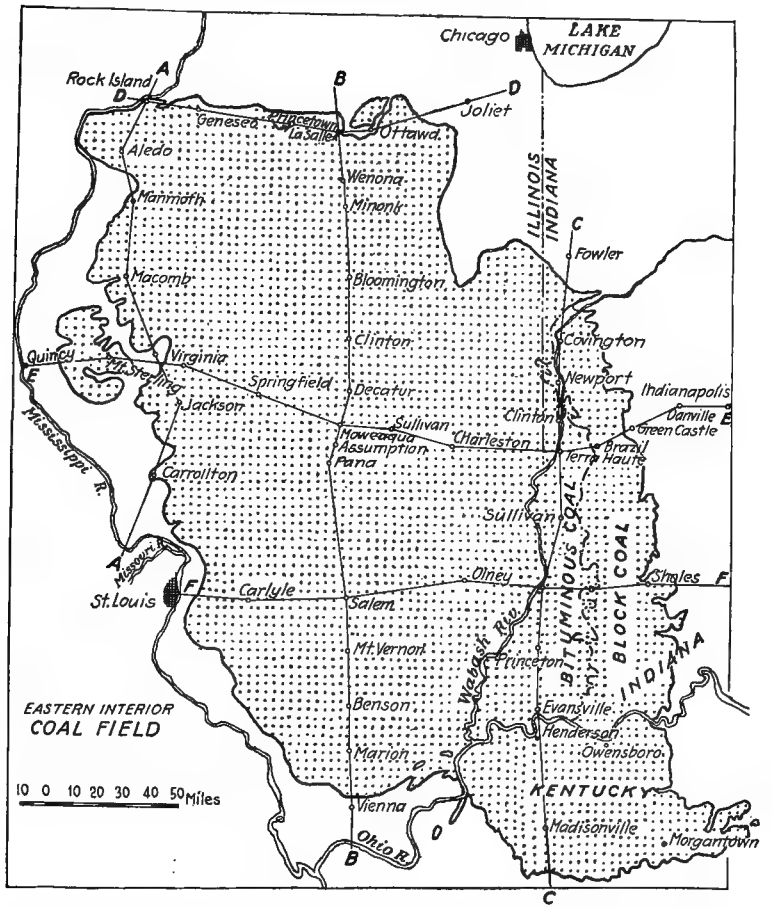


FIG. 37.—Sketch of eastern interior coal field. (*After Ashley, U. S. Geol. Survey.*)

Illinois.—The workable coals of Illinois are designated by the State Geological Survey Nos. 2, 3, 4, 5, 6, and 7. The coal beds

[1] There is some disagreement as to the correlation of coals in Illinois, Indiana and Kentucky. The reader is referred to papers of the Illinois state survey by DeWolf, Kay, and Lee, above cited, to a report by Logan of the Indiana survey in preparation and to a review by Ashley in Professional Paper No. 71, 1912, U. S. Geol. Survey pp. 466–468, and one by Ashley in Indiana Geol. Survey Ann. Rept. 33, pp. 13–150, 1909.

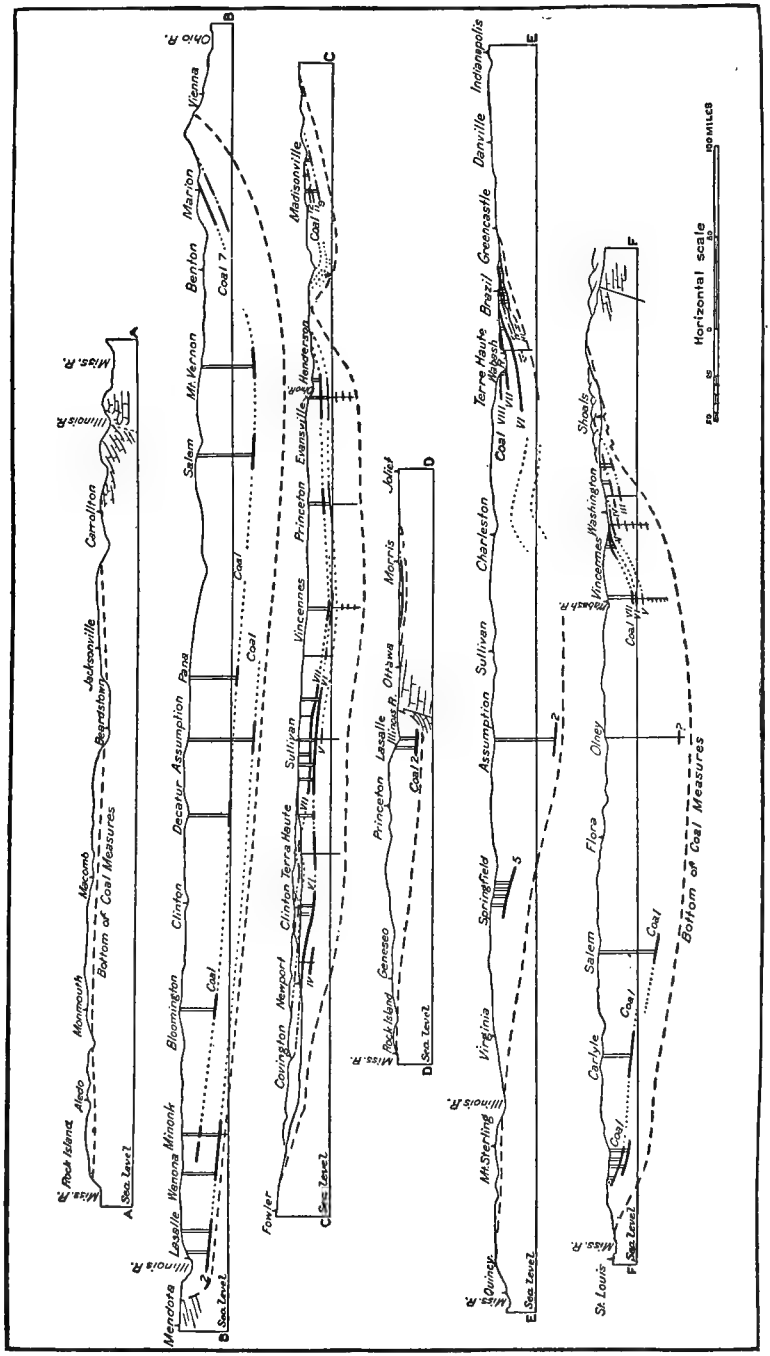


FIG. 38.—Structure sections of Eastern Interior coal field in Illinois, Indiana and Kentucky on lines *A–A*, *B–B*, *C–C*, etc. in Figure 37. (*Based on map by Ashley and other data.*)

are thick, and the product is good steam coal,[1] generally high in sulphur, compared to Appalachian coal. At Danville (Fig. 39) there are two beds of workable coal—the Danville coal (No. 7) and the Grape Creek coal (No. 6). Both of these beds are developed west of Vermilion River. In the developed portion of the field the Grape Creek coal has a thickness of 6 feet or more, especially in large areas south of Danville. The Danville bed lies about 80 feet above the Grape Creek bed. It has a thickness of 5 feet to 7 feet 6 inches over a large area west of Danville but thins toward the south. These coals crop out along the valley of Vermilion River but rapidly dip below drainage level on passing up the Middle Fork, reaching a depth of 200 feet or more at Muncie and Fairmount. At many mines the coal is taken out by stripping.

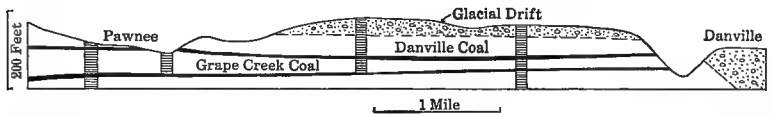


FIG. 39.—Section showing coal beds at Danville, Ill. (*Based on section by M. R. Campbell.*)

Northwest of Danville are the Wilmington and Streator fields. The first includes portions of Will, Grundy, and Lasalle counties. The coal worked is known as the Wilmington coal and is correlated as coal No. 2. It is a thin, irregular coal, averaging only about 3 feet in thickness, though locally measuring 6 feet.

The Streator coal (No. 7) is worked in Lasalle, Livingston, and Kankakee counties. It is much thicker than No. 2, ranging from 4 to 8 feet, with an average of about 5 feet. It ranges in depth from 65 to about 200 feet. Most of the local mines find coal at depths of 40 to 70 feet, usually in beds from 2 feet 3 inches to 3 feet 6 inches. West of the line of folding or faulting that passes near Lasalle the coal is deeper, being from 375 to 500 feet below the surface; it averages 3 feet 6 inches in thickness at most of the mines. In the southern part of Illinois the coal beds at many places are 3 to 7 feet thick and contain comparatively little waste.

Indiana.—In Indiana coal has been found at 20 horizons at least, as many as 17 beds having been struck in a single drilling within a vertical distance of 800 feet. Most of these are thin, but beds sufficiently thick to be workable occur at eight horizons

[1] For analysis see p. 20.

or more, though as a rule not more than three beds are workable at any one point, and usually not more than one, while large areas, amounting to a considerable percentage of the field, are not underlain by workable coal.

The coals of Indiana are subdivided into four groups—the Mansfield group, the lower part of the Wabash group, the upper part of the Wabash group, and the Merom group.

The rocks of the Mansfield group crop out in a belt from 5 to 20 miles wide along the eastern border of the field. They contain near their base one or two coals, which are workable over very small areas.

The rocks of the Wabash group crop out over a broad belt lying west of the outcrop the Mansfield. The coals are the well-known "Indiana block coal," (Fig. 37) the cannel coal of Cannelsburg, and semiblock coals. The coals lie in small basins that vary in extent from a few acres to several square miles. This variation is due to the irregular surface upon which they were deposited. The coals attain a thickness of 3 to 5 feet in the center of each basin, but thin out to a few inches between the basins. Notwithstanding this irregularity in thickness, it is possible to trace some of these coals over considerable areas. The coals of this group are cut by a series of cleavage planes which intersect nearly at right angles and divide the coal up into blocks with rectangular faces. It is from this feature that the name "block coal" is derived.[1]

Kentucky.—The workable coal of western Kentucky[1] is confined mainly to two beds, designated Nos. 9 and 11 by the Kentucky Geological Survey. Of these, No. 9 is the more persistent and furnishes the largest part of the product of this field. It occupies the whole or parts of seven or eight counties, including all of the field except its eastern portion and the southern or southwestern edge. It is also absent from a few small tracts where it has been cut out by reason of irregularities in the structure of the field. This bed has an average thickness of 5 feet, and rarely varies more than 6 inches from the average. As a rule it is found at depths of less than 200 feet, though at Eureka, Hopkins County, it is reported to be 400 feet below the surface.

From 40 to 100 feet above No. 9 is found the next most im-

[1] For analysis see p. 20.

portant bed, coal No. 11. This bed is much more irregular than No. 9, but at most of the mines at which it is worked it has a thickness of 6 feet or over. At Eureka its thickness reaches 7½ feet.

Western Interior Coal Field.—The Western Interior coal field (Fig. 40) occupies part of Iowa, Nebraska, Missouri, Kansas, Oklahoma, and Arkansas. The coal series is the Pennsylvanian.

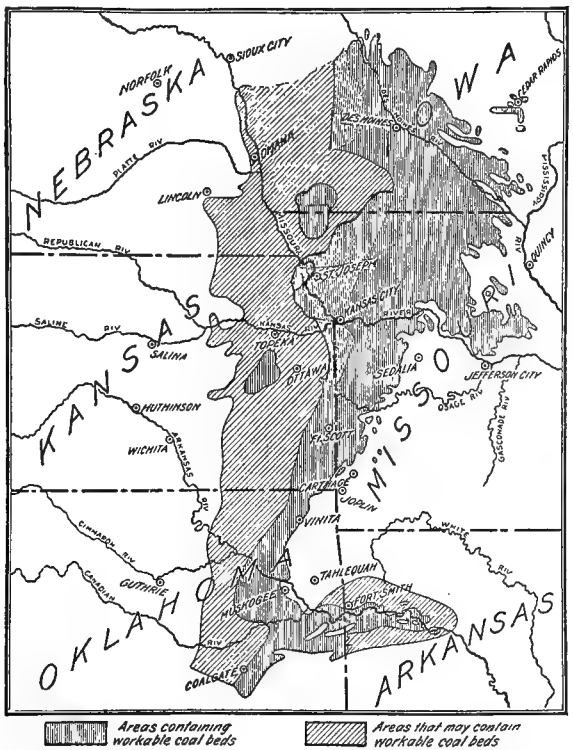


FIG. 40.—Map showing location of Carboniferous coal fields in Iowa, Missouri, Arkansas, Nebraska, Kansas and Oklahoma.

In the northern part of the field, in Iowa and Missouri, the rocks dip north, away from the Ozark Mountains; in Kansas they dip west, away from the Ozarks; and in northeastern Oklahoma they dip southwest. Toward the south, in Oklahoma and in western Arkansas, the coal beds are involved in the folding of the Ouachita and Arbuckle mountains. The coals are mainly of bituminous rank and are generally of somewhat lower grade than

Illinois coals. In Arkansas, where the rocks are folded, some of the coal has been converted to semianthracite.

Missouri.—The Pennsylvanian rocks in Missouri (Figs. 41, 42) dip north and west, away from the Ozark uplift, and occupy

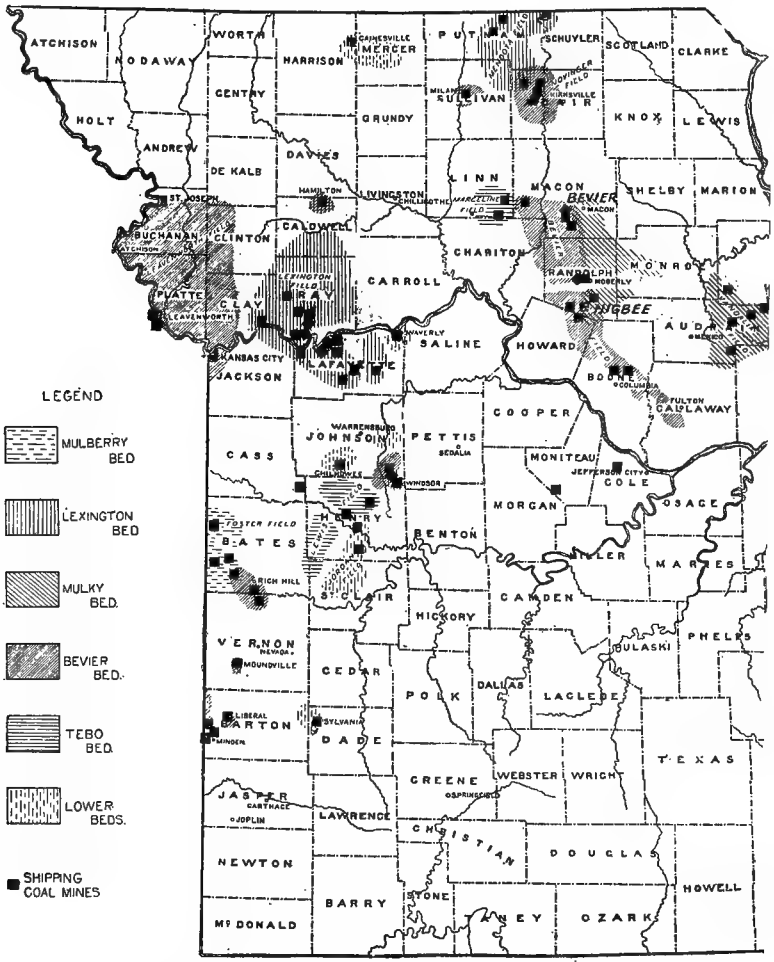


FIG. 41.—Outline map of coal-bearing part of Missouri showing position of commercial coal fields and mines. (*After Hinds, Mo. Bur. of Geol. and Mines.*)

a broad belt[1] whose total area is 23,960 square miles. The original tonnage of coal in Missouri is estimated at 76,225,000,000

[1] HINDS, HENRY: The Coal Deposits of Missouri. Mo. Bur. Geol. and Mines, *Second series*, vol. 11, pp. 1–503, 1912.

tons, of which less than one-half of 1 per cent. has been mined. The Pennsylvanian series contains all the coal beds in the State. It consists mainly of shale, sandstone, limestone, and clay. The valuable beds are in the Cherokee formation, the lowest of the Pennsylvanian series. The basal Cherokee beds were laid down unconformably on the irregularly eroded Mississippian surface. The principal beds are the Tebo, Bevier, Mulky, Lexington, and Mulberry. The beds contain bituminous coal of fair quality and are from 20 to 58 inches thick. Some of the beds are very persistent and extend into Iowa or Kansas.

The Bevier bed, named from the town of Bevier, Macon County, is the most productive in the State and has the largest reserves. At Bevier it is 54 inches thick and has a 1-inch parting near the base. The Bevier bed[1] extends southeastward through Higbee to a point near Fulton (Fig. 41).

In the Lexington field, near Kansas City, the Lexington coal is extensively mined. It is only about 20 inches thick but has a thin shale band above the coal and a firm limestone wall above the shale. The shale breaks in such a way that it is easily taken down to supply filling or pillars.

Thin coals have been worked at Vandalia and Mexico, but at both places the fireclays that are found just below the coal are more valuable than the coal. Pockets of

[1] For analysis see p. 20.

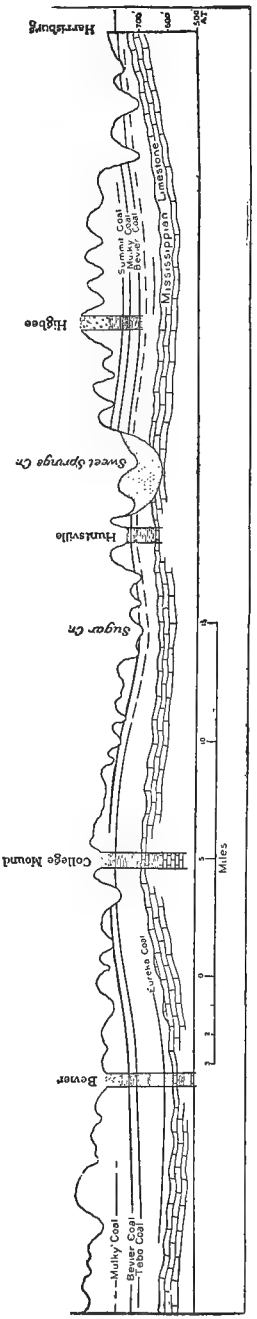


FIG. 42.—Cross-section from near Bevier, Macon County, Missouri, south through Randolph County, to northwestern Boone County, Missouri. (*After Hinds.*)

cannel coal are found at many places in Missouri. Some of them are very thick but cover only small areas, so that they have proved disappointing to those who attempted to exploit them on a large scale.

On the whole the coals of Missouri are not of high grade, and the beds are generally thinner than beds in the Illinois coal basin. Much Illinois coal is used in Missouri. The Missouri reserves are very large and will be more extensively worked when competing fields have exhausted their thicker seams.

Iowa.—In Iowa the coal fields extend over an area of 12,560 square miles. The coal-bearing rocks occupy almost the entire southern tier of counties[1] and extend northward beyond the center of the State. In western Iowa they are covered by Cretaceous rocks. The Paleozoic beds dip at very low angles and form the northern part of the Western Interior coal area. The coal beds are in the lower part of the Pennsylvanian series. In the south-central part of the State, in Wayne and Appanoose counties, the beds are regular and extend over large areas. In most of the State, however, many of the coal beds cover only a few thousand acres. The coal beds were deposited at many places on irregular surfaces so that the floor rises into the coal and cuts it out; at other places erosion channels filled with sandstone or with drift divide the coal.

The most extensive coal bed is the Mystic bed of the Appanoose-Wayne field. This bed, as stated by Hinds, is present over an area of 275,000 acres except where removed in old erosion channels. It is correlated with the Lexington bed of Missouri fields. In Iowa this bed is about 30 inches thick and is singularly regular in thickness over wide areas.

The coals of Iowa are bituminous[2] steam coals of fair quality, moderately high in ash, and like most of the Missouri coals they contain appreciable quantities of sulphur.

Kansas.—In Kansas the Pennsylvanian rocks[3] occupy a broad belt in the eastern part of the State, where they dip westward at low angles from the Ozark uplift. They consist of shale, limestone, sandstone, and coal beds. The total thickness of the

[1] HINDS, HENRY: The Coal Deposits of Iowa. Iowa Geol. Survey, vol. 19, pp. 25–396, 1908.

[2] For analysis see p. 20.

[3] HAWORTH, ERASMUS, and CRANE, W. R.: Special Report on Coal. Kan. Geol. Survey, vol. 3, pp. 1–336, 1898.

coal measures is estimated to be 3,000 feet. The coal beds are mainly in the lower part of the Pennsylvanian. The Cherokee formation, consisting largely of shale, is the most productive. The area of the coal fields is about 18,600 square miles. The individual beds of coal play out and overlap others. Some of the coal beds worked are 2 feet thick or less; others are 4 feet thick. The coal is of fair bituminous grade,[1] low in moisture and rather high in ash. At many places in Kansas the mantle rock is thin and the coal beds lie very close to the surface. Much of the coal is mined by stripping with steam shovels.

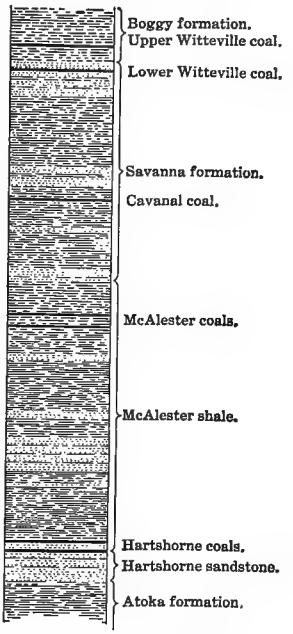


FIG. 43.—Section of coal bearing rocks of Oklahoma coal field. (*After Taff, U. S. Geol. Survey.*)

Oklahoma.—The coals of Oklahoma are all of Pennsylvanian age. The broad belt of Pennsylvanian strata that lies west of the Ozark uplift extends southwestward from Kansas into eastern Oklahoma and southward almost to the Arbuckle Mountains. A tongue of the Pennsylvanian rocks extends eastward from this belt along Arkansas River far into Arkansas. The field in Oklahoma occupies about 10,000 square miles. In this area many of the thin limestones so extensively developed in Kansas play out, and sandstone becomes more prominent.

A section of the coal-bearing formations in Oklahoma is given in Fig. 43. There are seven coal beds from 2 to 5 feet thick.

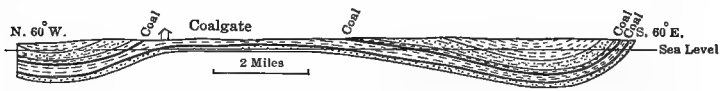


FIG. 44.—Cross-section of Carboniferous coal field near Coalgate, Okla. Horizontal and vertical scales are same. (*After Taff.*)

Other beds are locally thick enough to work. In the southern part of the field, north of the Arbuckle Mountains, the coals are extensively mined (Fig. 44). The coals[1] are relatively high in

[1] For analysis see p. 20.

fixed carbon for bituminous coals, as would be expected in rocks that are folded. They are also moderately low in ash, and some are very low in sulphur. The beds are in general thicker and the coals are better than most of the coals of the northern part of the Western Interior coal field.[1]

A small area of Pennsylvanian rocks is found south of the Arbuckle Mountains. The rocks are folded and faulted. The coal mined at Ardmore occurs in two benches 20 to 40 inches thick, separated by about 40 inches of shale.

Arkansas.—The Pennsylvanian coal measures extend from Oklahoma into Arkansas as a broad tongue along Arkansas River. The coal-bearing area is about 75 miles long, east and west, and about 50 miles wide at the State boundary (Fig. 40). The north border of the coal fields lies on the southern foothills of the Ozark Mountains. The south border is near the Ouachita Mountains, which extend from near Little Rock westward into Oklahoma.

Two coal beds are noteworthy—the Huntington coal, at the base of the upper or western division, and the Spadra coal, at the base of the eastern or lower division. These coal beds are from 3 to 6 feet thick. The coals[2] are low in moisture and in volatile hydrocarbons, and some are converted to semianthracite.[3]

Northern Texas.—In northern Texas[4] a great area of Pennsylvanian rocks extends northward about 250 miles, dipping west at low angles. This area contains several beds of bituminous coal. The coal is not of coking grade. The field is almost divided by a belt of Cretaceous rocks that extends across it. The part of the field lying north of this belt is called the Brazos field, from Brazos River. The part lying south is called the Colorado field. The Pennsylvanian series of northern Texas has been divided by Cummins into the Millsap, Strawn, Canyon, Cisco, and Albany formations. The top of the Millsap includes coal No. 1, which is mined at several places. The Cisco also contains several beds

[1] Taff, J. A.: The Southwestern Coal Field. U. S. Geol. Survey *Twenty-second Ann. Rept.*, part 3, pp. 373–389, 1902.

[2] Taff, J. A.: Arkansas Coal Field. U. S. Geol. Survey *Twenty-second Ann. Rept.* part 3, pp. 389–402, 1902.

[3] For analysis see p. 20.

[4] Taff, J. A.: North Texas Coal Field. U. S. Geol. Survey *Twenty-second Ann. Rept.*, part 3, pp. 402–409, 1912.

Cummins, W. F.: Report on the Geology of Northwestern Texas. Tex. Geol. Survey *Second Ann. Rept.*, pp. 359–554, 1890.

of coal, two of which are of considerable thickness. These are the Chaffin coal and coal No. 7.

Coal No. 1 is continuous for about 80 miles, and at many places it is 26 or 28 inches thick. It lies between hard shale and is easily mined. It is a good bituminous coal,[1] rather high in ash and sulphur.

The Chaffin coal is in the upper part of the coal measures, about 100 feet below coal No. 7. Where developed it is 20 inches thick and of good grade.

Coal No. 7 is in the Cisco group 300 feet above its base. The outcrop has been traced for 250 miles. It dips west at a low angle and is 12 to 42 inches thick, but where thickest it contains a layer of shale. It has a somewhat lower fuel ratio than coal No. 1. It is a good bituminous coal but too high in ash to make good metallurgic coke, and most of it is high in sulphur for making gas.

Santo Tomas Cannel Coal Field, Texas.—The Santo Tomas coal field lies on the Rio Grande between Laredo and Eagle Pass. The boundaries of the field have not yet been determined. The developed portion lies close to the Rio Grande, from 23 to 27 miles above Laredo.[2]

The coal deposit is probably the largest body of cannel coal of bituminous rank in the United States, if not in the world. It is not the high-moisture, soft brown lignite which is characteristic of coal beds of the same age in the central and eastern parts of the State, but a low-moisture coal almost as hard as anthracite, resisting weathering like an ordinary bituminous coal and sold on Government contracts under a guaranty of 12,500 British thermal units on "dry coal." The coal yields much gas when distilled at high temperatures and about 52 gallons of oil to the ton when distilled at low temperatures.

The Santo Tomas coal is of Eocene age. The bed is commonly from 24 to 36 inches thick and in most sections has a 2-inch parting near the middle. These figures do not take into account some 2 to 14 inches of bony coal at the bottom. From 14 inches to 20 feet above the coal is a thin persistent "rider" from 6 to 12 inches thick. This is commonly a bony coal but in places is fairly good.

[1] For analysis see p. 20.

[2] ASHLEY, H. G.: The Santo Tomas Cannel Coal, Webb County, Texas. U. S. Geol. Survey *Bull.* 691 pp. 251–270, 1918.

At the Pilote ranch, 25 miles above Santo Tomas, there are two beds of coal, the Santo Tomas above and the San Pedro bed below, separated by about 90 feet of strata. In mining it is necessary to remove much clay, which is carried to the surface. At some of the mines pyrite is brought out with the clay; weathering has produced spontaneous combustion in it, and the clay has been more or less burned.[1]

Texas and Louisiana Lignite Field.—A broad belt of rocks containing lignite extends northeastward from Laredo, Tex., almost to the Mississippi River (Fig. 22, p. 35). The lignites are mined for local use but are high in water.

Western Coal Fields.—In the western plains and Rocky Mountain region (Fig. 22, p. 35) coal is found at many places. During Cretaceous and early Tertiary time conditions were favorable for coal deposition throughout much of the territory between the 100th and 115th meridian, extending from Canada to New Mexico. The western part of this great area was thrown into mountains soon after the coal was formed. As a result of erosion, much of the coal was removed from the upfolds, so that almost all that remains occupies basins. This coal is mainly bituminous and subbituminous, and is high-grade fuel, although generally somewhat inferior to the eastern coal of Pennsylvanian age.

East of the Rocky Mountains, extending far to the east in the Dakotas, the coals occupy great areas, but they are of subbituminous and lignitic grade. The tonnage contained in several States is shown by Fig. 45.

Colorado.—The coals of Colorado (Fig. 46) are in the Dakota, the Mesaverde formation (Montana group, Upper Cretaceous), the Laramie, and the lower part of the Tertiary. The coals range from subbituminuous to anthracite. In general the subbituminous coal is found where the rocks are little disturbed and at a considerable distance from the great mountainous centers of uplift. The bituminous coal usually occurs in those parts of the fields that are near the bases of the mountains, and the anthracite, which is the product of local metamorphism, where a dike or sill of igneous rock has cut the coal or come into sufficiently close proximity to drive off its volatile constituents. The coal now produced is mainly of bituminous and subbituminous rank.

[1] ASHLEY, H. G.: *Op. cit.*, p. 270.

The Colorado coal fields lie in basins on the flanks of mountains and in the intermontane areas. There are three groups—the Eastern, Park, and Western. The Eastern group includes the Trinidad or Raton, Canon City, and South Platte fields; the Park group includes the Como, Middle Park, and North Park fields; the Western group includes the Durango field in

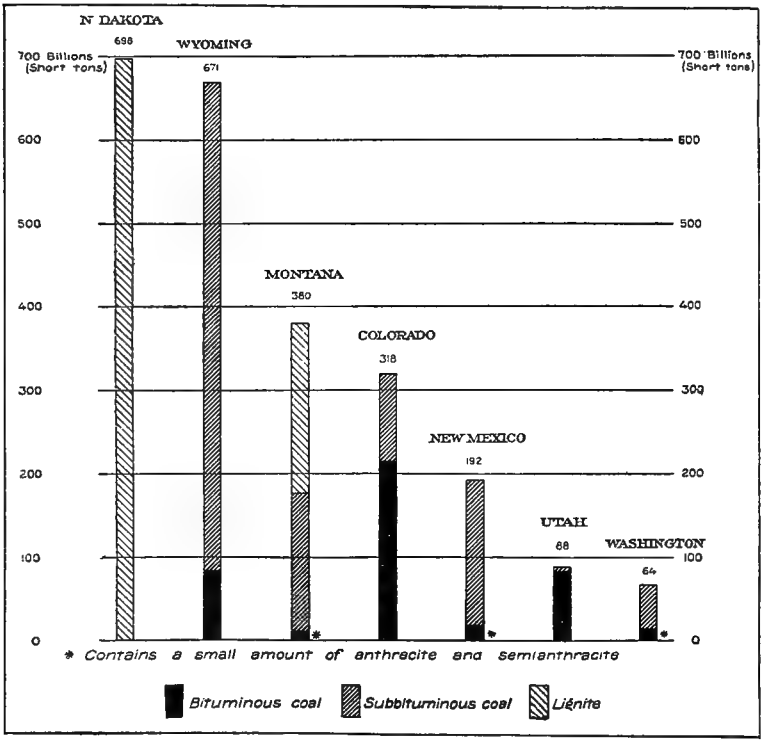


FIG. 45.—Chart showing tonnage of all grades of coal and lignite for certain western states. The totals are of workable coals within 3,000 feet of surface. (*From Stebinger, based on estimates by M. R. Campbell.*)

southwestern Colorado and the Book Cliffs, Grand Mesa, Crested Butte, Grand Hogback, Danforth Hills, and Yampa fields in northwestern Colorado.

The Raton field is one of the most extensively developed fields of the Rocky Mountain area. It lies about 50 miles south of Pueblo and extends into New Mexico, where it covers a broad area (See Fig. 53, p. 89.) The principal mining centers

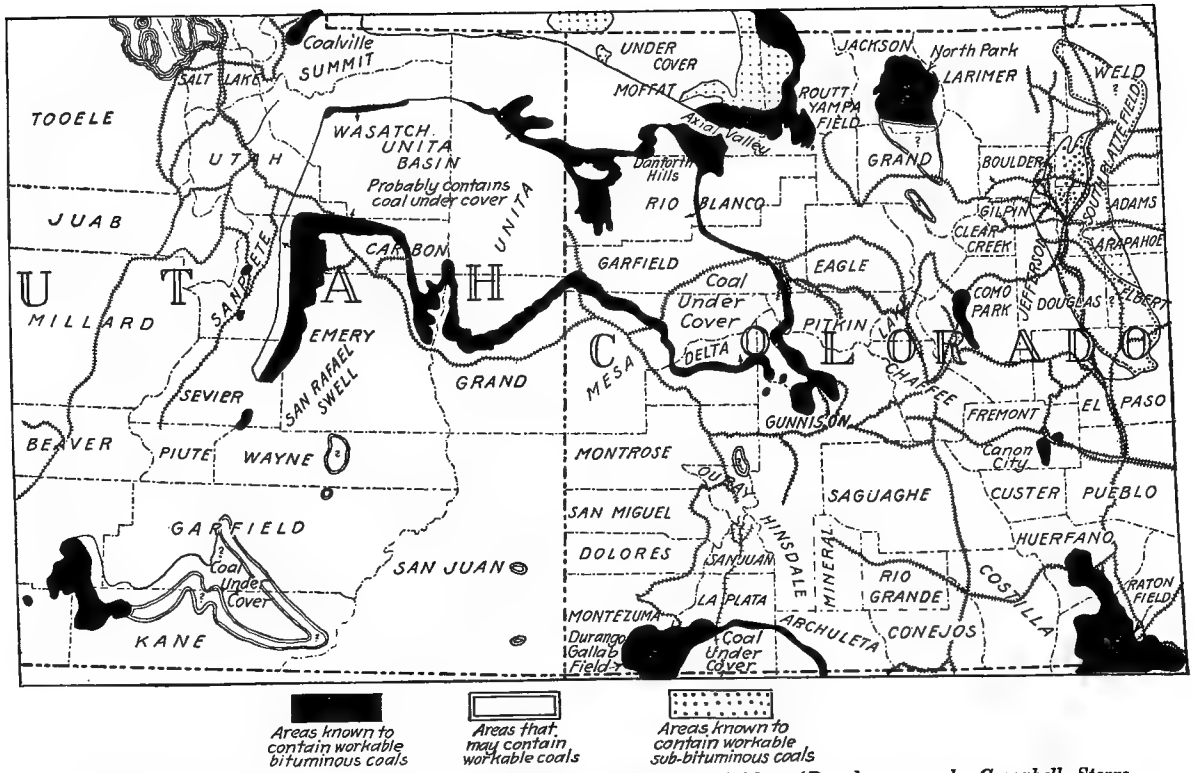


FIG. 46.—Outline map of parts of Colorado and Utah showing coal fields. (*Based on maps by Campbell, Storrs, Parker and others.*)

are Walsenburg and Trinidad, Colo., and Raton, N. M. The coals are of good bituminous rank[1] and are used for making coke, which is supplied to Pueblo iron and lead smelters and to other smelters in the West. The coals are in the Laramie formation, of the Upper Cretaceous (Figs. 47, 48). On the west margin of the field the rocks dip eastward at steep angles, on the east margin they dip westward at low angles, and near the center of the basin they lie flat. They are intruded by great dikes of

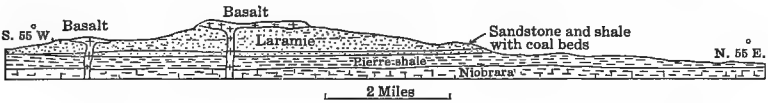


FIG. 47.—Section of Raton coal field 8 miles southeast of Trinidad, Colo. (*After Hills.*)

igneous rocks that are famous for their length and regular development. Some of the dikes form conspicuous ridges and may be followed along their strikes for miles. The lowest coal horizon is at the base of the Laramie. Another horizon is about 700 feet higher in the Laramie.

In the Trinidad district three or four beds are worked. These are in the lower part of the Laramie. Most of the mines have from 4 to 8 feet of coal. At Walsenburg three beds are worked. These have a total thickness of 16 feet. Where the dikes intrude the coal series the product as a rule is of superior quality.[2]

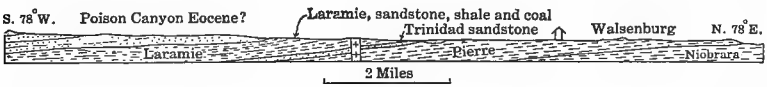


FIG. 48.—Section of Raton coal field 1½ miles north of Walsenburg, Colo. (*After Hills.*)

The Canon City coal field[3] lies in south-central Colorado, on the east front of the Rocky Mountains, in a small syncline. The beds are closely folded and locally on the west side of the

[1] For analysis see p. 20.

[2] HILLS, R. C.: U. S. Geol. Survey *Geol. Atlas*, folios 58 (El Moro); 68 (Walsenburg); 71 (Spanish Peaks).

STORRS, L. S.: The Rocky Mountain Coal Fields. U. S. Geol. Survey *Twenty-second Ann. Rept.*, part 3, pp. 424–431, 1902.

RICHARDSON, G. B.: The Trinidad Coal Field, Colorado. U. S. Geol. Survey *Bull.* 381, pp. 379–446, 1910.

[3] WASHBURN, C. W.: The Canon City Coal Field. U. S. Geol. Survey *Bull.* 381, pp. 341–378, 1910.

basin stand on edge. The coal is of Upper Cretaceous age and is a high-grade domestic fuel.[1]

The South Platte field is northeast of the Canon City field. It extends from the vicinity of Colorado Springs northward almost to the Wyoming line. The field is 140 miles long and 40 miles wide. The beds dip eastward away from the Front Range at relatively low angles. The coal beds are in the Laramie formation, and those worked are from 3 to 16 feet thick. Most of the coal is subbituminous but the coal north of Denver, on the western margin of the field, where the strata have been subjected to appreciable folding, is of fair grade, approaching bituminous coal in quality. The coal is high in moisture and volatile hydrocarbons and low in ash. It mines in blocks but slakes in storage and is not well adapted for long transportation. It competes with better Colorado coals on account of its nearness to market. The Laramie coal is mined also at Colorado Springs.[2]

The Como field is about 60 miles southwest of Denver and 15 miles southeast of Breckenridge. The field contains small blocks of "Laramie" strata, which are steeply tilted. The coal is a good steam coal and has been used at Leadville and Breckenridge.[3]

The North Park field occupies an intermontane area about 85 miles north of the Como field and 60 miles northwest of Boulder. The coal beds are in late Cretaceous or early Tertiary strata, which dip at relatively low angles. There are three beds, one from 4 to 5 feet thick, another 15 feet thick, and a third from 21 to 57 feet thick. The coals are mainly of subbituminous rank.[4]

The Yampa field,[5] Routt County, northwestern Colorado, contains valuable beds of coal which occupy an area of 1,200 square miles. The coal-bearing rocks belong to the Mesaverde formation (Cretaceous). They occupy a great basin and are folded and locally intruded by igneous rocks. There are three

[1] For analysis see p. 20.

[2] GOLDMAN, M. I.: The Colorado Springs Coal Field, Colorado. U. S. Geol. Survey *Bull.* 381, pp. 317–340, 1910.

[3] WASHBURNE, C. W.: The South Park Coal Field, Colorado. U. S. Geol. Survey *Bull.* 381, pp. 307–316, 1910.

[4] BEEKLY, A. L.: Geology and coal resources of North Park, Colorado. U. S. Geol. Survey *Bull.* 596, pp. 1–121, 1915.

[5] FENNEMAN, N. M., and GALE, H. S.: The Yampa Coal Field, Routt County, Colorado. U. S. Geol. Survey *Bull.* 297, pp. 1–92, 1906.

coal horizons in the Mesaverde. Some of the coal beds are from 4 to 9 feet thick. A section of the area is shown by Fig. 49. The bulk of the coal is bituminous and has a black, shining luster and more or less prismatic structure. The coal is sufficiently hard to be mined without a heavy percentage of slack and also to stand transportation. It does not weather badly and so is well fitted for domestic use and for the production of steam.[1] In heating value it compares favorably with the other better grades of western coals.[2]

The Danforth Hills coal district is separated from the Yampa field by 4 or 5 miles of lower rocks, that are brought to the surface on the crest of the anticline of Axial Valley. The coal-bearing rocks of the Danforth Hills are in the Mesaverde formation, and the coals are similar to the coals of the Yampa field.[3] From the Danforth Hills the outcrop of the Mesaverde formation extends southeastward for about 125 miles, crossing Grand River at Newcastle. The beds are 3 to 12 feet thick. The coal is of good bituminous grade and is mined at Newcastle, in Pitkin County.

In western Gunnison County near Crested Butte the beds are highly folded and intruded by igneous rocks, and the coal is converted to anthracite.

From Gunnison County westward the beds extend over 200 miles to a point beyond Price, Utah. The rocks dip north and come to the surface again in the northern part of Uinta Basin, Utah, where they are exposed near Vernal. In Mesa

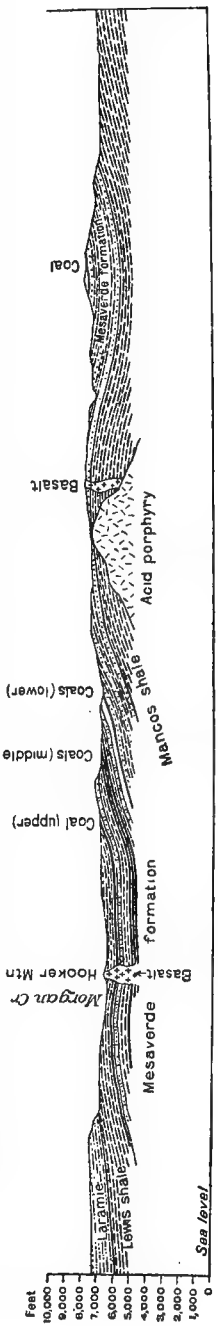


FIG. 49.—Section of Yampa coal field, Routt County, Colorado. (*After Gale, U. S. Geol. Survey.*)

[1] CAMPBELL, M. R.: Character and Use of the Yampa Coals. U. S. Geol. Survey *Bull.* 297, pp. 82–92, 1906.

[2] For analysis see p. 20.

[3] GALE, H. S.: Coal Fields of the Danforth Hills and Grand Hogback in Northwestern Colorado. U. S. Geol. Survey *Bull.* 316, pp. 264–301, 1907.

County, Colorado, the coal is mined for locomotive fuel for the Uintah Railway.[1]

The Durango-Gallup field[2] is in southwestern Colorado and northwestern New Mexico. In Colorado the rocks dip south, away from the San Juan uplift. They rise again to the south, and form a great shallow structural basin. Coal has been mined from the Dakota, the Mesaverde, and the Laramie, but the better grades come from the Mesaverde. The Mesaverde coal near Durango has been mined to supply coke for Durango smelters.

In the region around Mancos the Dakota sandstone, in the area north of the town, yields a very impure coal of bituminous rank, and the Mesaverde formation, in the hills south of the town a purer coal of somewhat lower rank.[3]

Utah.—The great belt of coal-bearing rocks that extends westward from Crested Butte, Colo., beyond the State line continues westward almost to central Utah (Fig. 46). This region is known as the Book Cliffs,[4] from a range of hills that form the south rim of the Uinta Basin. Near the border of the State there are several beds of coal in the Mesaverde formation. The beds in general dip north at low angles and are not greatly deformed by folding. The coals are thick and of good bituminous rank, although in general they are mined with considerable slack.

In a mine near Thompson, a station on the Denver & Rio Grande Railroad between Grand and Green rivers, the coal beds dip 2°–3° N. The best coal bed averages 4 feet in thickness.[5]

[1] Richardson, G. B.: The Book Cliffs Coal Field between Grand River, Colorado, and Sunnyside, Utah. U. S. Geol. Survey *Bull.* 316, pp. 302–320, 1907.

[2] Shaler, M. K.: A Reconnaissance Survey of the Western Part of the Durango-Gallup Coal Field of Colorado and New Mexico. U. S. Geol. Survey *Bull.* 316, pp. 375–426, 1907.

Taff, J. A.: The Durango Coal district, Colorado. U. S. Geol. Survey *Bull.* 316, pp. 321–357, 1907.

Gardner, J. H.: The Coal Field between Durango, Colorado and Monero, New Mexico. U. S. Geol. Survey *Bull.* 341, pp. 352–363, 1909.

[3] Collier, A. J.: Coal South of Mancos, Montezuma County, Colorado. U. S. Geol. Survey *Bull.* 691, p. 293–310.

[4] Richardson, G. B.: Reconnaissance of the Book Cliffs Coal Field, Between Grand River, Colorado, and Sunnyside, Utah. U. S. Geol. Survey *Bull.* 371, pp. 1–54, 1909.

[5] Clark, F. R.: Coal Near Thompson, Grand County, Utah. U. S. Geol. Survey *Bull.* 541, pp. 453–477, 1912.

Farther west, in Carbon and Emery counties, the coal belt is extensively developed. Mines are operated at many places, among them Castlegate, Sunnyside, Winterquarters, and Clear Creek. This region[1] yields much the larger part of the coal produced in Utah, and its coal is coked for use in the great smelters that center around Salt Lake. The dominating structural feature of the region is the San Rafael Swell, a great anticline that pitches north. The beds lie on the flanks of the anticline. The coal is of medium-grade bituminous rank and occurs in the Mesaverde formation. Southward from Castledale the beds in the Mancos formation, below the Mesaverde, are coal-bearing. The Ferron sandstone member contains several beds of good bituminous coal in western Emery County and northeastern Sevier County.

At Coalville,[2] 30 miles northeast of Salt Lake City, subbituminous coal is mined from Cretaceous beds, probably belonging to the Frontier formation of the Colorado group. The beds are folded and in places overturned, the dominating feature of the structure being an overturned anticline. The coal occurs at three horizons. The best bed is the "Wasatch," which is from 5 to 12 feet thick and in places is free from bone and shale partings.

South of the Uinta Mountains, on the north side of the great structural basin known as the Uinta Basin, the Cretaceous rocks crop out in the region near Vernal. A coal bed 7 feet thick is mined for local use near Cockleburr. This is good bituminous coal of the Mesaverde formation. Other mines are opened about 6 miles west of Vernal. The beds are in the Mancos formation,[3] which dips south, in places 30° or more. It contains subbituminous coal.

[1] TAFF, J. A.: The Pleasant Valley Coal District. U. S. Geol. Survey *Bull.* 316, pp. 338–358, 1907.

LUPTON, C. T.: Geology and Coal Resources of Castle Valley in Carbon, Emery, and Sevier Counties, Utah. U. S. Geol. Survey *Bull.* 628, pp. 1–88, 1916.

[2] WEGEMANN, C. H.: The Coalville Coal Field, Utah. U. S. Geol. Survey *Bull.* 581, part 2, pp. 161–183, 1913.

[3] GALE, H. S.: Coal Fields of Northwestern Colorado and Northeastern Utah. U. S. Geol. Survey *Bull.* 341, pp. 283–315, 1909.

LUPTON, C. T.: The Deep Creek District of the Vernal Coal Field, Utah. U. S. Geol. Survey *Bull.* 471, pp. 579–594, 1912.

The Blacktail Mountain field[1] is in the west part of the Uinta Basin, about due west of Vernal. Coal is found in both the Mancos and Mesaverde. The beds dip south at high angles. The coal seams are thick and numerous. The coal is of low bituminous rank.

In southern Utah,[2] in Iron, Kane, and Washington counties, Cretaceous beds in a large area are folded to form a basin. Coals are found in the Colorado group. The coals are high in fixed carbon, but they contain much ash. This field is nearest to the southern California market, and if coals low in ash are found they will be in good demand.

Wyoming.—The coals of Wyoming (Fig. 50) are in the main bituminous and subbituminous coal of rank. They are found in the Lower Cretaceous, Upper Cretaceous, and Tertiary series. In southwestern Wyoming, at Kemmerer and vicinity, in Uinta County, excellent coals are mined from the Benton strata of the Cretaceous, which are steeply folded.[3] The coal beds are from 4 to 7 feet thick, and the coals are of bituminous rank. These coals are low in ash and are among the best in the Rocky Mountain fields. The Adaville formation, at horizons above the Benton, contains coal beds of great thickness but of lower rank than the Benton coals. One bed contains 18 feet of workable coal in two benches.

In central Lincoln County, Wyoming, just east of Pocatello, Idaho, coal is found in the Frontier formation (Benton), in the Adaville formation (uppermost Montana and Lower Laramie), and in the Evanston formation. The beds are closely folded so that they dip at high angles. The best coals are in the Frontier formation.[4] They are high-grade bituminous coals and are mined from beds 3 to 7 feet or more thick. Some of the coals are nearly as high in heating value as Appalachian coals.

The Rock Springs district is in southwestern Wyoming, on the Union Pacific Railroad. It is one of the principal fields in Wyoming and supplies coal for locomotives and other purposes.

[1] Lupton, C. T.: The Blacktail (Tabby) Mountain Coal Field, Wasatch County, Utah. U. S. Geol. Survey *Bull.* 471, pp. 595–628, 1910.

[2] Richardson, G. B.: The Harmony, Colob, and Kanab Coal Fields, Southern Utah. U. S. Geol. Survey *Bull.* 341, pp. 379–400, 1909.

[3] Veatch, A. C.: Geography and Geology of a Portion of Southwestern Wyoming. U. S. Geol. Survey *Prof. Paper* 56, pp. 1–178, 1907.

[4] Schultz, A. R.: Coal Fields of a Portion of Central Uinta County, Wyoming. U. S. Geol. Survey *Bull.* 316, pp. 212–241, 1907.

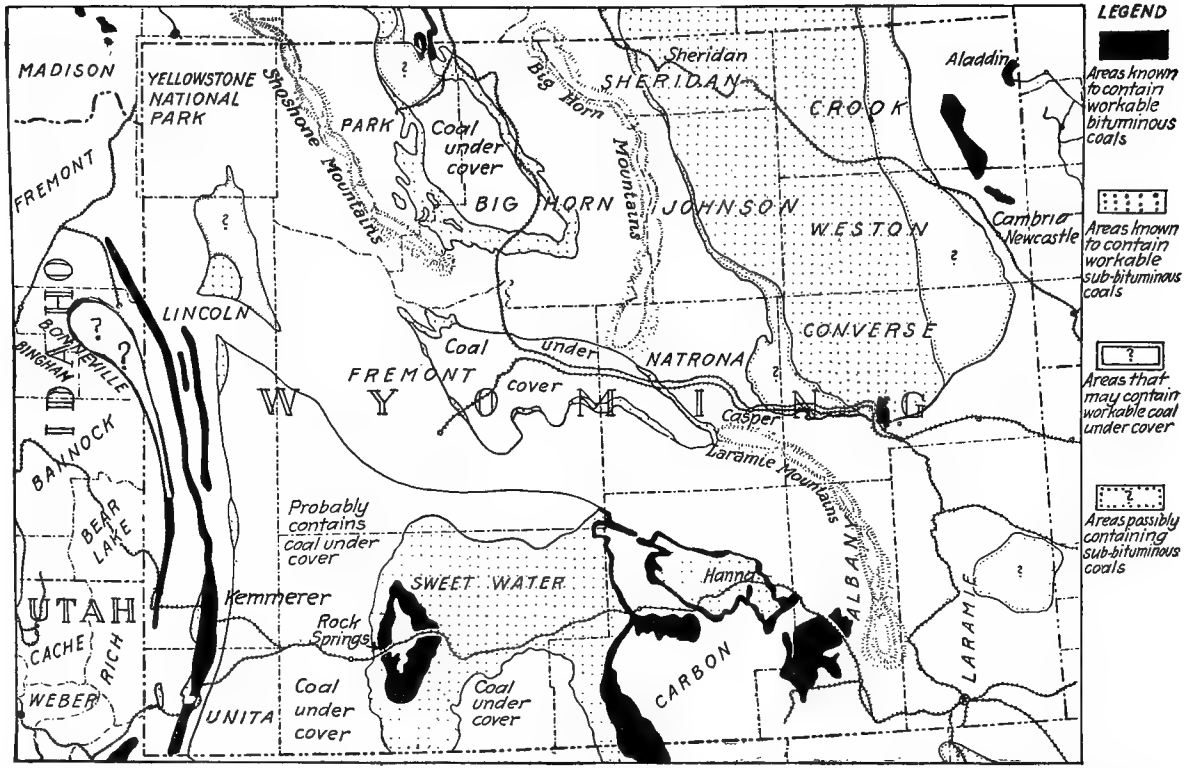


FIG. 50.—Outline map of Wyoming and part of Idaho showing position of coal fields. (*Based on maps by Campbell, Parker, Veatch, Schultz and others.*)

East of Rock Springs is the top of a broad structural dome,[1] from which the beds dip away in all directions at angles of 5° to 30°. Coal is found in the Mesaverde, the Laramie, and the Wasatch (Eocene). The Rock Springs group, the lowest part of the Mesaverde, contains the best coal. The formation is the same and the coal similar to the coal of the Yampa field, in Colorado. There are twelve beds from 2 to 10 feet thick. The coal is subbituminous to bituminous and one of the best steam fuels[2] in the West. It is extensively mined near Rock Springs.

In east-central Carbon County,[3] at Hanna, on the Union Pacific Railroad, coal is mined from the Upper Laramie formation. The rocks are closely folded and dip at high angles. Some of the coal beds are 30 feet thick. The coals are not so good as the Benton coals of Uinta County and are probably inferior to the Rock Springs coal. In the Mesaverde formation, below the Laramie, excellent coal is found, but the beds are thin. The Lewis formation of the Montana also contains good coal.

The Sheridan field is in northern Wyoming, east of the Big Horn Mountains. The strata containing the coal beds are of the Fort Union formation[4] (lower Eocene) and dip eastward at low angles. The beds are from 3 to 12 feet thick and at places considerably thicker. The coal is subbituminous. When exposed to weather it breaks down rapidly, but if protected from rain in box cars it will stand transportation. It is low in ash and fairly high in moisture.[5] It is used extensively as steam coal.

The Glenrock field[6] is in Natrona and Converse counties, a short distance north and east of Caspar. The field is at the foot of the Front Range of the Rocky Mountains, and the beds dip to the northeast. Coal is found in the Montana formation of the Cretaceous, especially in the upper two-thirds of the formation, and also in the Fort Union of the Eocene. The

[1] Schultz, A. R.: The Northern Part of the Rock Springs Coal Field, Sweetwater County, Wyoming. U. S. Geol. Survey *Bull.* 341, pp. 256–282, 1909.

[2] For analysis see p. 20.

[3] Veatch, A. C.: Coal Fields of East Central Carbon County, Wyoming. U. S. Geol. Survey *Bull.* 316, pp. 244–260, 1907.

[4] Taff, J. A.: The Sheridan Coal Field, Wyoming. U. S. Geol. Survey *Bull.* 341, pp. 123–150, 1909.

[5] For analysis see p. 20.

[6] Shaw, E. W.: The Glenrock Coal Field, Wyoming. U. S. Geol. Survey *Bull.* 341, pp. 151–164, 1901.

principal mining is done on the Glenrock-Big Muddy zone, at the base of the Fort Union. At Big Muddy two beds are worked; one is 4 feet 8 inches thick, the other 3 feet 6 inches. At Glenrock a 5-foot bed is worked. The coal is subbituminous. It is not good locomotive fuel, and most of it is used for domestic heating.

On the west side of the Black Hills uplift bituminous coals are mined from the Lakota formation of the Lower Cretaceous.[1] At Cambria, near Newcastle, bituminous coal of good quality is mined from a bed 4 to 7 feet thick. Coke was made from the coal to supply the precious-metal smelter at Deadwood, S. Dak., before the smelter was dismantled. On the north slope of the Black Hills at Aladdin,[2] near the State line, a good steam coal is mined from the Lakota. The beds are from 2 to 5 feet thick and are faulted.

Idaho.—Idaho contains comparatively little coal. Some is found in southeastern Idaho[3] in the Grays Lake region and also in the Horseshoe district, which is in southeastern Fremont County. Most of the coal beds that have been exploited are of Cretaceous age, belong to the Frontier formation, and represent the northward extension of the coal beds which are extensively developed in southwestern Wyoming. The coal is bituminous and rather free from impurities. Most of the coal is badly shattered, as would be expected in a region where so much faulting has taken place. As a result of this shattered condition a large percentage of the coal in mining comes out fine.

In the Horseshoe district, southeastern Fremont County, there are thick beds of good bituminous coal,[4] but they are steeply folded and extensively faulted. According to Woodruff, they will not become an important factor in the coal production of the Rocky Mountains.

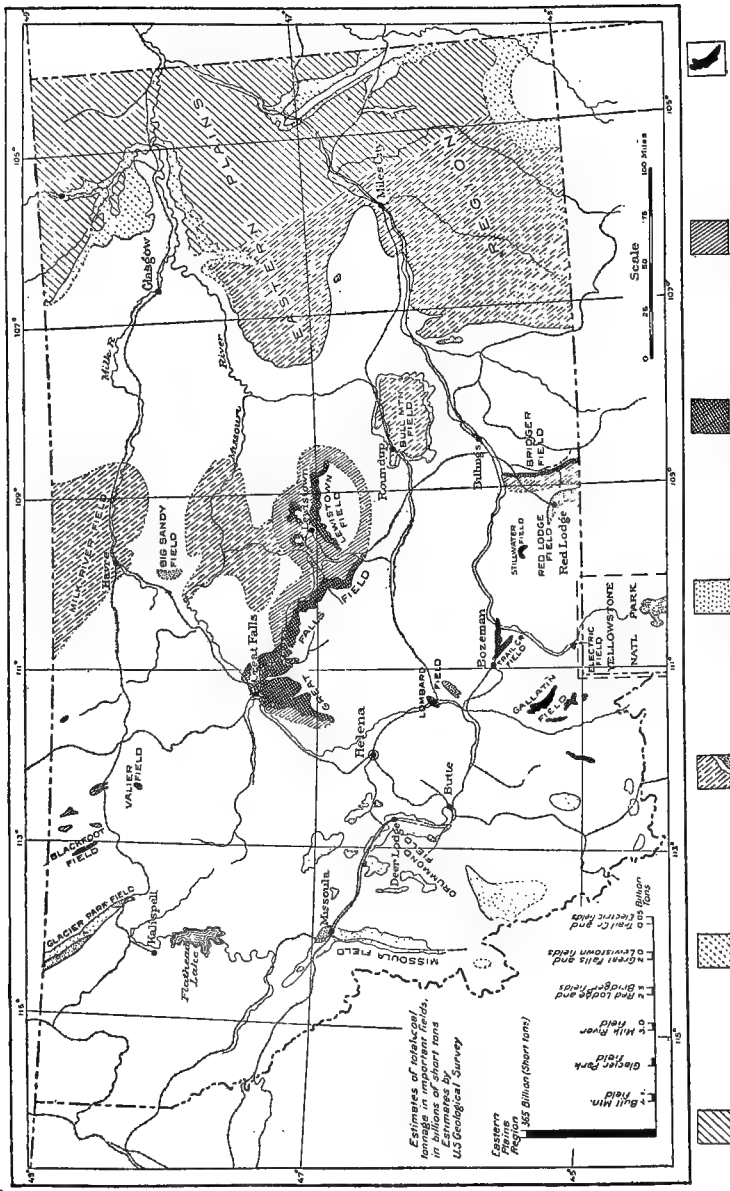
[1] Stone, R. W.: Coal Near the Black Hills, Wyoming and South Dakota. U. S. Geol. Survey *Bull.* 499, pp. 1–66, 1912.

Darton, N. H.: The Coal of the Black Hills, Wyoming. U. S. Geol. Survey *Bull.* 260, pp. 429–433; also U. S. Geol. Survey folio 107, Newcastle, 1904.

[2] Darton, N. H., and O'Harra, C. C.: U. S. Geol. Survey folio 128 (Aladdin), 1905.

[3] Schultz, A. R.: A Geologic Reconnaissance for Phosphate and Coal in Southeastern Idaho and Western Wyoming. U. S. Geol. Survey *Bull.* 680, pp, 1–71, 1918.

[4] Woodruff, E. G.: The Horseshoe District of the Teton Basin Coal Field, Fremont County, Idaho. U. S. Geol. Survey *Bull.* 541, pp. 379–385, 1914.


Lignite.
Probable lignite area.
Sub-bituminous coal.
Probable area of sub-bituminous coal
Bituminous coal.
Probable area of bituminous coal.
Anthracite or semi-anthracite, with probably a large percentage of bituminous coal.
Scale
Miles
Glasgow
Miles City
Roundup
Billings
Bozeman
Helena
Butte
Missoula
Kalispell
Great Falls
Lewistown
Red Lodge
Red Lodge Field
Stillwater Field
Big Sandy Field
Valier Field
Blackfoot Field
Glacier Park Field
Milk River Field
Bull Mtn. Field
Judith Basin Fields
Musselshell Field
Pryor Mtn. Field
Yellowstone Nat'l. Park
Electric Peak Fields
Gallatin Field
Dry Fork Field
Deer Lodge Field
Missoula Field
Lombard Field
Spring Creek Field
Spring Coulee Field
Spring Hill Field
Spring Valley Field
Spring Water Field
Spring Dale Field
Spring Brook Field
Spring Meadow Field
Spring Grove

Lignite is mined from the Tertiary (probably Payette) about 20 miles north of Boise,[1] and in the Goose Creek district,[2] Cassia County southern Idaho.

Montana.—The coal-bearing formations of Montana[3] (Fig. 51) range in age from the Kootenai of the Lower Cretaceous to the Tertiary. A generalized geologic section after Stebinger is shown in Fig. 52.

The Bridger field is in Carbon County, in the southern part of Montana. It occupies a long, narrow area, the northern part of which is developed near the towns of Bridger, Coalville, and Joliet. About 120 square miles is underlain with workable coal, which is in the Eagle sandstone of the Montana group.[4] The beds dip west. Three beds of coal are worked at

[1] Bowen, C. F.: Coal at Horseshoe Bend and Jerusalem Valley, Boise County, Idaho. U. S. Geol. Survey *Bull.* 531, pp. 245–251, 1913.

[2] Bowen, C. F.: Lignite in the Goose Creek district, Cassia County, Idaho. U. S. Geol. Survey *Bull.* 531, pp. 252–262, 1913.

[3] Stebinger, Eugene: The Coal Fields of Montana. Am. Inst. Min. Eng. *Trans.* vol. 46, pp. 889–919, 1913.

[4] Washburne, C. W.: Coal Fields on the Northeast Side of the Big Horn Basin, Wyoming, and Bridger, Mont. U. S. Geol. Survey *Bull.*, 341, pp. 165–199, 1909.

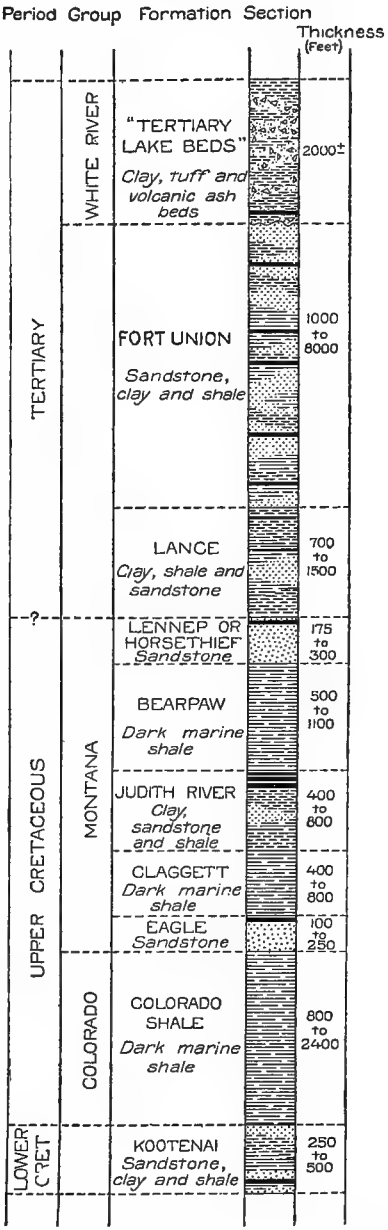


Fig. 52.—Generalized geologic section of the Cretaceous and Tertiary formations in Montana showing the stratigraphic positions of the principal coal horizons. (*After Stebinger.*)

different places in the area. The bed at Bridger is 4½ feet thick and contains two bone partings. The coal is of bituminous rank.

At Red Lodge and Bear Creek,[1] in Carbon County, about 50 miles southwest of Billings, coal is mined from the Fort Union formation, which contains a total of 71 feet of coal in layers over 3 feet thick. One bed is 12 feet thick. The coal is subbituminous and is harder than that of Sheridan, Wyo., which is found in beds of the same age.

The Stillwater field, about 35 miles northwest of Red Lodge,[2] is a small area of 10 square miles. The coal is in the Eagle sandstone and is similar to that at Bridger. The field is much broken by faults.

The Electric or Cinnabar field[3] is in southwestern Park County, near the gate of the Yellowstone National Park. The coal is found in beds of the Montana group which are highly tilted and faulted. The principal coal bed is 40 inches thick. The coal is of good bituminous grade and has been mined for making coke to supply Montana smelters.

The Trail Creek field is north of the Electric field and extends from a point east of Livingston almost to Bozeman. At Cokedale, 7 miles west of Livingston, coal was formerly mined extensively and used for making coke. A 4½-foot bed was followed down a dip of 55°. The coal is in the Montana group and is of good bituminous grade. One fork of the coal formation of the Trail Creek district extends southeastward from the west end of the field. The coal there is bituminous but of rather lower grade than the Livingston coal.[4]

In the Great Falls region coal is found in the Kootenai formation (Lower Cretaceous) about 60 feet above its base. The rocks dip 4°–10° NE. The coal is not continuous but lies in three areas which together embrace 316 square miles.[5] The beds

[1] Woodruff, E. G.: The Red Lodge Coal Field, Montana. U. S. Geol. Survey *Bull.* 341, pp. 92–107, 1909.

[2] Stebinger, Eugene,: *Op. cit*, p. 906.

[3] Calvert, W. R.: The Electric Coal Field, Park County, Montana. U. S. Geol. Survey *Bull.* 471, pp. 406–422, 1912.

[4] Calvert, W. R.: The Livingston and Trail Creek Coal Fields, Park, Gallatin, and Sweet Grass Counties, Montana. U. S. Geol. Survey *Bull.* 471, pp. 384–405, 1912.

[5] Fisher, C. A.: The Great Falls Coal Field, Montana. U. S. Geol. Survey *Bull.* 316, pp. 161–173, 1907.

mined are generally 3 to 6 feet thick. The coals are medium grade bituminous, rather high in ash and sulphur, but are well situated to command a good market in Montana.

The Lewistown field[1] lies east of the Great Falls field. The coal is near the base of the Kootenai formation and is of the same age as the Great Falls coal. The coal series circles the Big Snowy Mountains, an anticlinal range in southern Fergus County. Not all parts of the field, however, are known to contain workable coal. The Kootenai is a medium-grade bituminous coal.

An area east of the Bearpaw Mountains,[2] called the Cleveland coal field, comprises 423 square miles in which coal is found in the upper part of the Judith River formation. The coal is pockety, and the beds in general are thin. The coal is of low rank.

In the Big Sandy field,[3] west of the Bearpaw Mountains, coal is found in the Eagle sandstone and Judith River formations, both Cretaceous, and also in the Fort Union formation of the Tertiary. The Cretaceous coals are thin and of low grade. The Tertiary coal is a low-grade subbituminous coal somewhat inferior to that of the Great Falls district. It is mined at Mackton, where the beds are folded and faulted.

The Bull Mountain coal field[4] is in Yellowstone and Musselshell Counties, in the south-central part of Montana, for the most part between practically parallel stretches of Musselshell and Yellowstone rivers. The area of coal-bearing rocks is roughly elliptical in form, about 50 miles long. The field came into prominence in 1906–7, soon after the construction of the Pacific coast extension of the Chicago, Milwaukee & St. Paul Railway, when mining was begun on a large scale on the Roundup bed, and the towns of Roundup and Klein have grown up largely as a result of this industry.

The coal is high-grade subbituminous coal and is generally

[1] CALVERT, W. R.: The Lewistown Coal Field, Montana. U. S. Geol. Survey *Bull.* 341, pp. 108–122, 1909.

[2] BOWEN, C. F.: The Cleveland Coal Field, Blaine County, Montana. U. S. Geol. Survey *Bull.* 541, pp. 338–355, 1914.

[3] BOWEN, C. F.: The Big Sandy Coal Field, Chouteau County, Montana. U. S. Geol. Survey *Bull.* 541, pp. 356–378, 1914.

[4] WOOLSEY, L. H., RICHARDS, R. W., and LUPTON, C. T.: The Bull Mountain Coal Field. U. S. Geol. Survey *Bull.* 647, pp. 1–218, 1917.

LUPTON, C. J.: The Eastern Part of the Bull Mountain Coal Field, Montana. U. S. Geol. Survey *Bull.* 431, pp. 163–189, 1911.

uniform in character. The Bull Mountain field is estimated to cover 405,175 acres and to contain 4,073,360,000 tons of coal.

The important coal-bearing formation of the Bull Mountains is the Fort Union, which belongs to the Eocene series.

In western Montana there are many coal fields, although most of them are not extensively developed. In the Gallatin field anthracite and semianthracite are found. The beds are probably of lower Montana age. The coals are in a syncline, and beds from 4 to 6 feet thick are known. In the Lombard field,[1] between Helena and Bozeman, coals are found probably in the Kootenai formation. The strata are much broken and, according to Stebinger, some of the coal is essentially graphite.

Lignites are found in Tertiary lake beds in the vicinity of Deer Lodge, Drummond, and Missoula. In the Blackfoot field, near the Canadian border, bituminous coal occurs in the Horsethief sandstone. The coal is of excellent quality, but the structure is complicated. The thickest coal bed, according to Stebinger, is 3½ feet thick.

In the Milk River field, near Havre, workable coals of subbituminous grade are found near the top of the Judith River formation.[2]

The eastern plains region[3] is the largest field in Montana and

[1] Rowe, J. P.: Montana Coal and Lignite Deposits. Montana University *Bull.* 37, 1906.

[2] Pepperberg, L. J.: The Milk River Coal Field, Montana. U. S. Geol. Survey *Bull.* 381, pp. 82–107, 1910.

[3] Beekly, A. L.: The Culbertson Lignite Field, Montana. U. S. Geol. Survey *Bull.* 471, pp. 319–359, 1912.

Bowen, C. F. The Baker Lignite Field, Custer County, Montana. U. S. Geol. Survey *Bull.* 471, pp. 202–226, 1912.

Calvert, W. R.: Geology of Certain Lignite Fields in Eastern Montana. U. S. Geol. Survey *Bull.* 471, pp. 187–201, 1912.

Hance, J. H.: The Glendive Lignite Field, Montana. U. S. Geol. Survey *Bull.* 471, pp. 271–283, 1912.

Herald, F. A.: The Terry Lignite Field, Custer County Montana. U. S. Survey *Bull.* 471, pp. 227–270, 1912.

Rowe, J. P.: Some Montana Coal Fields. *Am. Geologist*, vol. 32, pp. 369–380, 1903.

——— Montana Coal and Lignite Deposits. *Montana University Bull.* 37, 1906.

——— Montana Coal and Lignite Deposits. *Min. World*, vol. 26, 1907.

——— Some Economic Geology of Montana. *Montana University Bull.* 50, 1908.

contains much more coal than all the other fields combined. Nearly all the coals are in the Fort Union formation. The strata are nearly flat or only gently flexed. In the eastern part of the region the coal is true lignite and shows the grain of the wood. Toward the west across this region, as stated by Stebinger, the lignite changes gradually into a black, shiny, subbituminous coal. The change is so gradual that probably no two observers would agree as to the place where the line of division should be drawn. As the brown color disappears the lignite loses more and more of its woody character. Near Glendive it is black but lusterless; at Miles City its color is a little more pronounced, and much of it is black and shining; on the extreme western edge of the area it has practically lost all traces of its woody structure and exhibits a brilliant luster throughout, being a true subbituminous coal.

The Little Sheep Mountain coal field in eastern Montana, is 24 to 30 miles wide from north to south and extends westward about 60 miles from the neighborhood of Terry.[1]

The Fort Union contains many thick beds. The coal is on the border line between lignite and subbituminous coal. Many of the coal beds have become ignited at some time since the early Pleistocene and in burning have baked and partly fused the overlying strata. The underlying strata are also generally somewhat affected, but in many places the coal has not burned entirely to the base of the bed, so that the underlying rocks are more or less protected. The burning thus usually bevels back the outcrop, progressing farthest back at the top of the bed. In general, where there is a cover of more than 10 or 20 feet the coal will not burn more than 50 or 75 feet back from the outcrop, although exceptionally the burning may extend farther. Where the cover is less than 10 feet the burning may extend throughout a large area. The effects produced depend entirely upon the quality and amount of the coal. Several thick beds, separated by 10 or 20 feet of rock, may produce very extensive results.

North Dakota and South Dakota.—The Great Plains coal field, which lies partly in eastern Montana, extends eastward into the Dakotas. The largest area is in North Dakota,[2] which contains

[1] ROGERS, G. S.: The Little Sheep Mountain Coal Field, Dawson, Custer, and Rosebud Counties, Montana. U. S. Geol. Survey *Bull.* 531, pp. 159–227, 1913.

[2] LEONARD, A. G.: The North Dakota-Montana Lignite Area. U. S. Geol. Survey *Bull.* 285, pp. 316–330, 1906.

more coal than any other western State. The coal is all subbituminous coal and lignite and is not extensively mined except for local use The beds[1] are thick, numerous, and extensive, but the water content is high, generally running about 31 per cent. The ash is low, from 3 to 8 per cent., volatile matter about 28 per cent., and fixed carbon 37 per cent.

The coal generally checks on drying and does not stand transportation well. Methods for dehydrating and partly coking the coal have been under investigation. If they are commercially successful, the field will become a very important source of fuel.[2]

New Mexico.—There are several coal bearing areas in New Mexico (see Fig. 53), the most productive of which is the southern part of the Raton field,[3] in northeastern New Mexico, already mentioned in the treatment of Colorado fields. Good bituminous coal is produced in the New Mexico part of the Raton field, and anthracite is found near intrusive rocks. The bituminous coal makes good metallurgic coke and is used extensively in the Southwest, for smelting copper, lead, and silver ores of Arizona and Mexico. The district is served by several railroads. The coal is in the upper part of the Upper Cretaceous ("Laramie"). There are five workable beds of coal, but the principal developments are on the lowest one.

The Durango-Gallup field[4] of Colorado and New Mexico (see p. 72) is a great irregular basin, as already noted. Coal is found in the Dakota, Mancos, Mesaverde, and "Laramie" of the Upper Cretaceous. Near Gallup coal is mined from the Mesaverde. It is good subbituminous coal and as stated by

[1] LEONARD, A. G., and SMITH, C. D.: The Sentinel Butte Lignite Field, North Dakota and Montana. U. S. Geol. Survey *Bull.* 341, pp. 15–35, 1909.

LEONARD, A. G.: The Lignite Deposits of North Dakota. North Dakota University *Quart. Jour.*, vol. 6, no. 3, pp. 234–240, 1916.

[2] WILDER, F. A.: N. D. Geol. Survey, *Second Ann. Rept.*, 1902.

TODD, J. E.: Geology of South Dakota. S. D. Geol. Survey, vol. 1, pp. 96–99, 199, 1894.

[3] STORRS, L. S.: The Rocky Mountain Coal Fields. U. S. Geol. Survey *Twenty-second Ann. Rept.*, part 3, pp. 415-471, 1901.

[4] SCHRADER, F. C.: The Durango-Gallup Coal Field of Colorado and New Mexico. U. S. Geol. Survey *Bull.* 285, pp. 241–258, 1906.

SHALER, M. K.: Reconnaissance of the Western Part of the Durango-Gallup Coal Field of Colorado and New Mexico. U. S. Geol. Survey *Bull.* 316, pp. 375–426, 1907.

GARDNER, J. H.: The Coal Field Between Gallup and San Mateo, New Mexico. U. S. Geol. Survey *Bull.* 341, pp. 364–378, 1909.

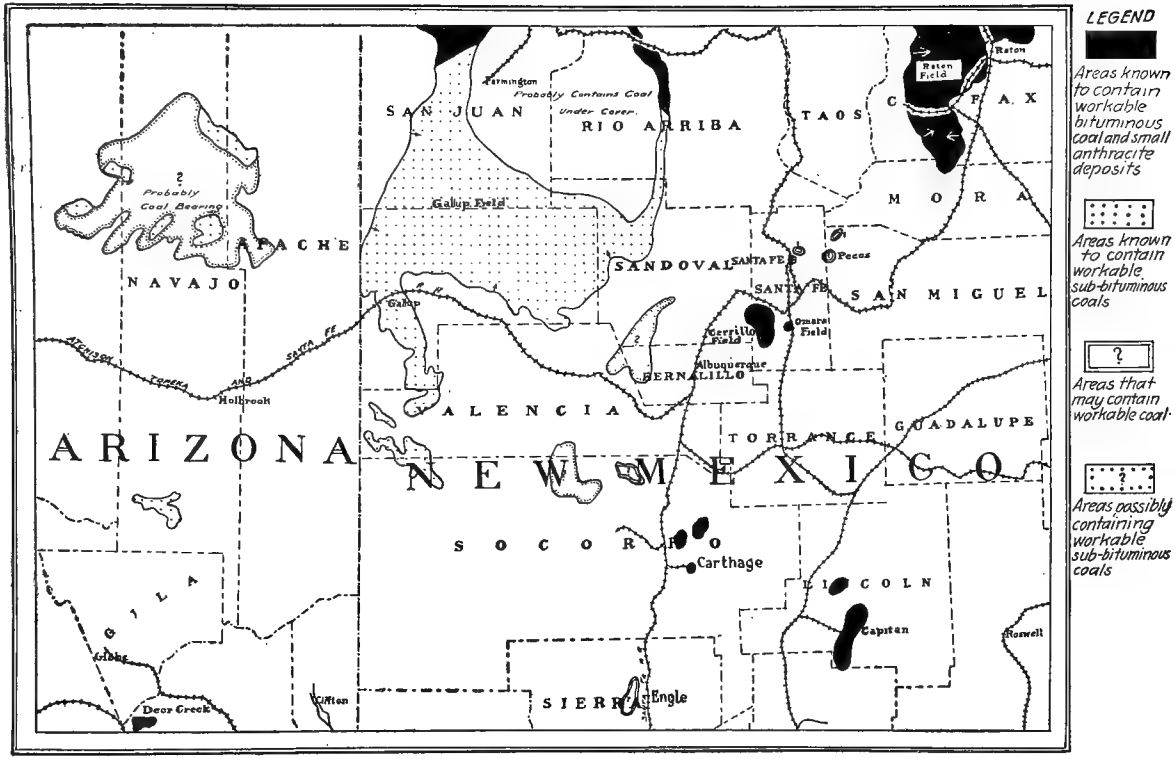


FIG. 53.—Outline map of parts of New Mexico and Arizona showing position of coal fields. (*After Campbell, Storrs, Parker and others.*)

Shaler occurs in beds up to 8½ feet thick. It is mined to supply a local demand for locomotive fuel.

The Cerrillos coal field is on Galisteo Creek in central New Mexico west of the Rocky Mountain axis. The field is irregular in outline and extends from the town of Galisteo westward about 12 miles to a point about a mile west of Madrid. Special interest attaches to the Cerrillos[1] field, not so much because of its present productiveness as because it is one of the oldest producers in western America.

The coal-bearing rocks occupy the center of a basin, in the eastern part of which they dip toward the west, away from the axis of the Rocky Mountains, and at the west end they dip toward the east, away from the axis of the Sandia Mountains. On the north the rocks were steeply upturned by the intrusion of the igneous rocks of the Cerrillos Mountains and on the south by the Ortiz laccolith. The coal is in the Mesaverde formation. The beds worked are from 2 to 5 feet thick. The coal has low moisture, high carbon, and low ash. Three grades of coal are found in the Cerrillos field—anthracite, coking bituminous, and noncoking bituminous. The White Ash bed, where it is least affected by the intrusive igneous rock, contains coking bituminous coal, which in former years was produced from the White Ash mine. An igneous rock is reported as lying 30 to 50 feet or more above the coal in this mine.

The Uña del Gato field, Sandoval County, is 15 miles south of Cerrillos and 14 miles east of Algodones. The coal-bearing rocks are probably the same as those of the Cerrillos field[2] (see Fig. 53), but the rocks in the intervening country are concealed. In the Hagan mine good bituminous coal is mined from a 4-foot bed.

In the Omara[3] field, Santa Fe County, the coal is of Cretaceous age. Two beds are worked, and one of them is 4½ feet thick. The area known to contain coal is very small.

On Pecos River about 5 miles above the town of Pecos a 20-inch seam of bituminous coal was opened at the Gould & Thomas

[1] Lee, W. T.: The Cerrillos Coal Field, Santa Fe County, New Mexico. U. S. Geol. Survey *Bull.* 531, pp. 285–312, 1913.

[2] Campbell, M. R.: Uña del Gato Field, Sandoval County, New Mexico. U. S. Geol. Survey *Bull.* 316, pp. 427–430, 1907.

[3] Gardner, J. H.: Isolated Coal Fields in Santa Fe and San Miguel Counties, New Mexico. U. S. Geol. Survey *Bull.* 381, pp. 447–451, 1910.

mine.[1] The coal occurs in the lower part of the Pennsylvanian series.

Coal is found in the west-central part of Lincoln County near the headwaters of the Rio Hondo. The beds are highly deformed and are intruded by dikes, which have converted the coal locally to a noncombustible coke or slag. The coal, which is of Cretaceous age,[2] is bituminous and burns freely but leaves much clinker and ash.[3] It has been mined at Capitan, on a spur of the El Paso & Southwestern Railway.

The Carthage coal field is in Socorro County, near Socorro. The coal-bearing rocks are of Cretaceous age, probably Montana, and the region is much complicated by faulting.[4] The Carthage coal bed is 5 feet thick. The coal ranks with the best of the Southwest and is said to make excellent coke. Difficulties are encountered in mining the coal owing to the faults, which make exploration expensive and uncertain.

The Engle coal field, 70 miles south of the Carthage district, is of uncertain value.[5]

Arizona.—In northeastern Arizona, in the Navajo and Hopi Indian reservations, there is a large undeveloped area of Cretaceous coal,[6] in the Black Mesa field. This field is a flat synclinal basin. Although the coal is higher in fixed carbon than that of the Gallup field, it occurs in rather thin benches alternating with bone and shale, and it is comparatively high in ash. At the Tuba mine three beds are mined for local consumption; the thickest one measures 3½ feet.

The Deer Creek field, in eastern Pinal County, in the midst of the copper-producing country, in as irregular synclinal trough of deformed Cretaceous rocks that contain bituminous coal rather high in ash.[7] In places the coal is cut by igneous dikes and

[1] GARDNER, J. H.: *Op. cit.*, p. 449.

[2] FISHER, C. A.: Coal Fields of the White Mountain Region, New Mexico. U. S. Geol. Survey *Bull.* 225, pp. 292–294, 1904.

[3] CAMPBELL, M. R.: Coal in the Vicinity of Fort Stanton Reservation, Lincoln County, New Mexico. U. S. Geol. Survey *Bull.* 316, pp. 431–434, 1907.

[4] GARDNER, J. H.: The Carthage Coal Field, New Mexico. U. S. Geol. Survey *Bull.* 381, pp. 452–460, 1910.

[5] LEE, W. T.: The Engle Coal Field, New Mexico. U. S. Geol. Survey *Bull.* 285, p. 240, 1906.

[6] CAMPBELL, M. R., and GREGORY, H. E.: The Black Mesa Coal Field, Arizona. U. S. Geol. Survey *Bull.* 431, pp. 229–238, 1911.

[7] CAMPBELL, M. R.: The Deer Creek Coal Field, Arizona. U. S. Geol. Survey *Bull.* 225, pp. 240–258, 1904.

metamorphosed. Some of the coal makes a coke of fair grade, but according to Campbell the beds are only from 24 to 30 inches thick.

Near Pinedale, in southern Navajo County, coal is found also in Cretaceous strata. One bed, according to Veatch,[1] is locally about 30 inches thick. Thicker beds are found above it, but they contain bone and are high in ash.[1]

Nevada.—The Coaldale field, Nevada, is about 30 miles west of Tonopah, on the Tonopah & Goldfield railroad.[2] The coals are of Tertiary age, probably Miocene. The beds are thin, are extensively faulted and contain high ash. The aggregate coal in an exposed section may amount to 2 or 3 feet, but it is usually made up of thin streaks. The coal does not slack rapidly and is reported to be a fairly good steaming coal. Its value is uncertain.

California.—California contains very little coal and depends largely upon oil for fuel, though some coal is brought in from other States and imported by sea from foreign countries.

Coal has been mined in Stone Canyon in the Diablo Range, Monterey County.[3] The bed which is of lower Miocene age, rests on serpentine and is highly tilted. It is about 15 feet thick and dips 70° NE. The coal is a good bituminous steam coal and high in sulphur.[4] It does not slake on drying. The air dried coal has a heating value of 12,727 British thermal units.

Bituminous coal is mined also at Trafton, San Benito County. It is higher in ash than the Stone Canyon coal,[5] but like that coal it carries much sulphur.

There are also several other small areas containing coal in California.

Oregon.—The coal fields of Oregon are of small extent and contain only coals of low grade. The principal field is the Coos Bay field, Coos County, in the southwestern part of the State.

[1] Veatch, A. C.: Coal Deposits near Pinedale, Navajo County, Arizona. U. S. Geol. Survey *Bull.* 431, pp. 239–240, 1911.

[2] Hance, J. H.: The Coaldale Coal Field, Esmeralda County, Nevada. U. S. Geol. Survey *Bull.* 531, pp. 313–322, 1913.

[3] Arnold, Ralph: Coal in the Mount Diablo Range, Monterey County, California. U. S. Geol. Survey *Bull.* 285, pp. 223–225, 1906.

[4] Campbell, M. R.: Coal of Stone Canyon, Monterey County, California. U. S. Geol. Survey *Bull.* 316, pp. 435–438, 1906.

[5] Campbell, M. R.: Coal in San Benito County, California. U. S. Geol. Survey *Bull.* 431, pp. 243–247, 1910.

This field[1] occupies an area of about 230 square miles. It is a structural basin, and the rock beds are thrown into folds and dip at high angles. They belong to the Arago formation of the Eocene. There are several beds of coal, which are in general from 2 to 3 feet thick. The coal is a high subbituminous coal rather low in moisture and high in ash.

The Rogue River valley coal field[2] is about 75 miles southeast of the Coos Bay field. The coal is of very low grade and high in ash.

Washington.—The coal fields of Washington are in the western part of the State. There are four principal fields—The North Puget Sound field, in Skagit and Whatcom Counties; the South Puget Sound field, in King and Pierce Counties; the southwestern field, in Lewis and Cowlitz Counties; and the Roslyn field, in Kittitas County. In these fields the coal is in shale and sandstone strata of Eocene age. The beds are in general folded or tilted at high angles. The coals include lignite, subbituminous, and bituminous grades. There are many beds, and some of them are 13 feet or more thick, but as a rule the thick beds contain shale or bone partings.

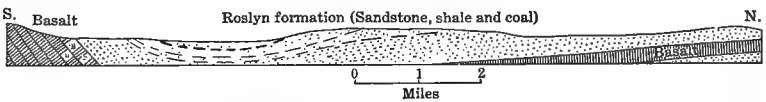


FIG. 54.—Section of rocks east of Roslyn in Roslyn coal field, Washington. The coal is in the Roslyn (Eocene) formation which rests on basalt. (*After G. O. Smith, U. S. Geol. Survey.*)

The Roslyn field, in Kittitas County, is an area of folded sedimentary and igneous rocks. Coal is found in the Roslyn formation, of Eocene age (Fig. 54). This formation consists of sandstone with argillaceous phases and of coal. The principal coal bed is the Roslyn bed, although several other beds of workable thickness are known. The coal series occupies an elongated structural basin. The coal is good coking coal of bituminous grade. Its percentage of fixed carbon increases from the center of the basin-like fold toward the west, where the folding is more intense, as the heart of the Cascade Range is approached.[3]

[1] DILLER, J. S. and PISHEL, M. A.: Preliminary Report on the Coos Bay Coal Field, Oregon. U. S. Geol. Survey *Bull.* 431, pp. 190–228, 1911.

[2] DILLER, J. S.: The Rogue River Coal Field, Oregon. U. S. Geol. Survey *Bull.* 341, pp. 401–405, 1909.

[3] SMITH, G. O. and CALKINS, F. C.: Snoqualmie Folio (No. 139), *Geol. Atlas,* U. S.

The Wilkeson-Carbonado[1] coal-mining district is southeast of Tacoma, in King and Pierce Counties, on the extreme northwestern foothills of Mount Rainier. Coal is developed at several mines, all in the Puget formation of the Eocene. The rocks are complicated by folding and faulting and dip at high angles (Fig. 55). Much of the coal is bituminous. It is fairly high in ash and low in moisture and has a high heat value.

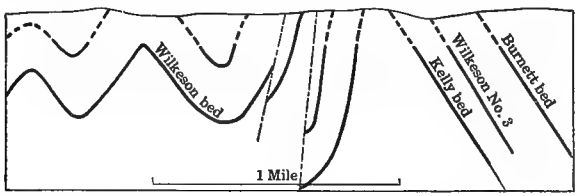


FIG. 55.—Section showing coal beds in Wilkeson-Carbonado district near Tacoma, Wash. (*After Willis, U. S. Geol. Survey.*)

Alaska.—Coals are found in Alaska[2] at many places (Fig. 56). They range in age from the Mississippian to Tertiary. The Bering River and Matanuska fields contain the largest amount of high-grade coal. At Cook Inlet there is a large field of Tertiary lignite, and on Alaska Peninsula Cretaceous coals are found on Chignik Bay and Herendeen Bay. In northern Alaska the Cape Lisburne field is the most important.

The Bering river field, near Controller Bay, occupies 45 square miles. It contains anthracite and semibituminous coal of Tertiary age, and some of the coal is of coking quality. Coal beds 15 feet thick are known. The rocks are steeply folded and faulted. The coal is low in ash and water and high in fixed carbon. It compares favorably with the better coals of the Appalachian region.

The Matanuska Valley field[3] is 175 miles northwest of the

[1] WILLIS, BAILEY and SMITH, G. O.: Tacoma Folio (No. 54), U. S. *Geol. Atlas*, 1899.

SMITH, E. E.: Coals of the State of Washington. U. S. Geol. Survey *Bull.* 474, pp. 167–192, 1911.

[2] MARTIN, G. C.: The Alaska Coal Fields. U. S. Geol. Survey *Bull.* 314, pp. 40–46, 1907; Geology and Mineral Resources of the Controller Bay Region, Alaska. U. S. Geol. Survey *Bull.* 335, pp. 1–141, 1908.

[3] MARTIN, G. C., and MERTIE, J. B.: Mineral Resources of the Upper Matanuska and Nelchina Valleys. U. S. Geol. Survey *Bull.* 592, pp. 273–299, 1914.

Bering River field. The coal-bearing area covers 100 square miles and the rocks are of Jurassic and Eocene age. The coal beds dip at high angles and where closely folded contain bituminous

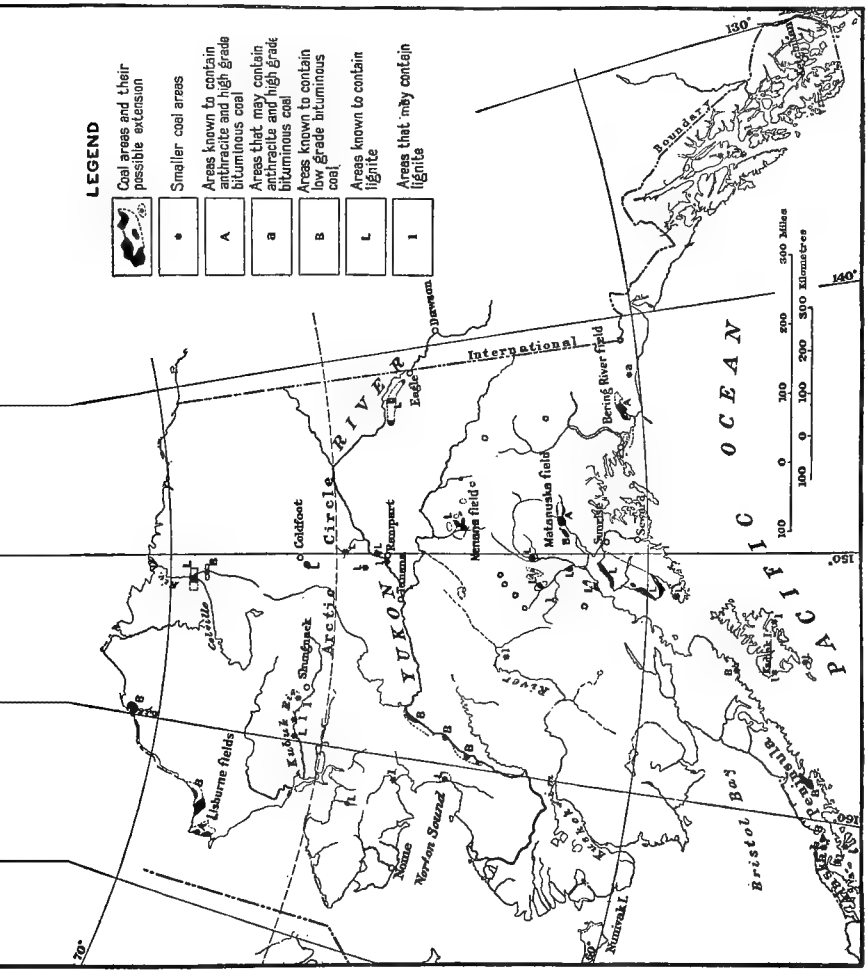


FIG. 56.—Map showing coal deposits of Alaska. (*After Brooks.*)

and anthracite coal. In the southwestern part of the field the beds are little disturbed and contain low-grade coals.

Canada.—Canada has many large areas of bituminous and subbituminous coal.[1] The coal fields are situated in both the

[1] DOWLING, D. B.: The Coal Fields and Coal Resources of Canada. *Coal Resources of the World*, vol. 2, pp. 439–532, 1913.

Atlantic and Pacific coast regions, in the mountains of British Columbia, in Alberta, and in the central interior plains region (see Fig. 57). The coal fields of both coasts and certain areas in the Rocky Mountains are being actively exploited; large areas in Alberta and Saskatchewan are little explored. The bituminous coals of Nova Scotia and New Brunswick occur in the Carboniferous system. They are of good grade and are used extensively in producing power for manufacturing, in railway and marine transportation, and in the reduction of iron ore. They are well situated with respect to the great iron deposits of Conception Bay, Newfoundland. On the Pacific coast coals are mined for local use and for export. In the interior fields the coals of the mountainous regions of eastern British Columbia and western Alberta are of the highest grade.

The situation in Canada with respect to coal resources is noteworthy. The Dominion possesses more coal in proportion to its population than any other large nation in the world, but most of the deposits are not well located with respect to centers of industry and population. The great provinces of Quebec and Ontario have very little coal. The country lying north of the upper St. Lawrence River and the Great Lakes is far from the Canadian coal fields and depends largely on coal imported from the United States. On the other hand, Canada exports much coal to the United States on both the Atlantic and Pacific seaboards.

In Nova Scotia, Carboniferous coals of Pennsylvanian age are found in several fields. The principal coal areas are in Sydney (Fig. 58), Inverness, Pictou, and Cumberland Counties. Coking coals are found in Sydney and Pictou. The Wabana iron ores of Newfoundland are shipped to Sydney, where there is an extensive iron-making industry. The Nova Scotia coals are exported also to the United States. New Brunswick contains coal measures, but they are less valuable than those of Nova Scotia.[1]

The Sydney field has an area of 57 square miles on land and a large area also below the sea. Some of the coal is mined from the under-sea beds. There are at least six coal beds 3 feet or more thick. They are comparatively regular and dip at low angles. The coal is bituminous coal of good quality. It makes good coke and is also a good steam coal. In the Inverness field, on the

[1] Dowling, D. B.: Coal Fields and Coal Resources of Canada. Canada Geol. Survey *Mem.* 59, pp. 1–174, 1915.

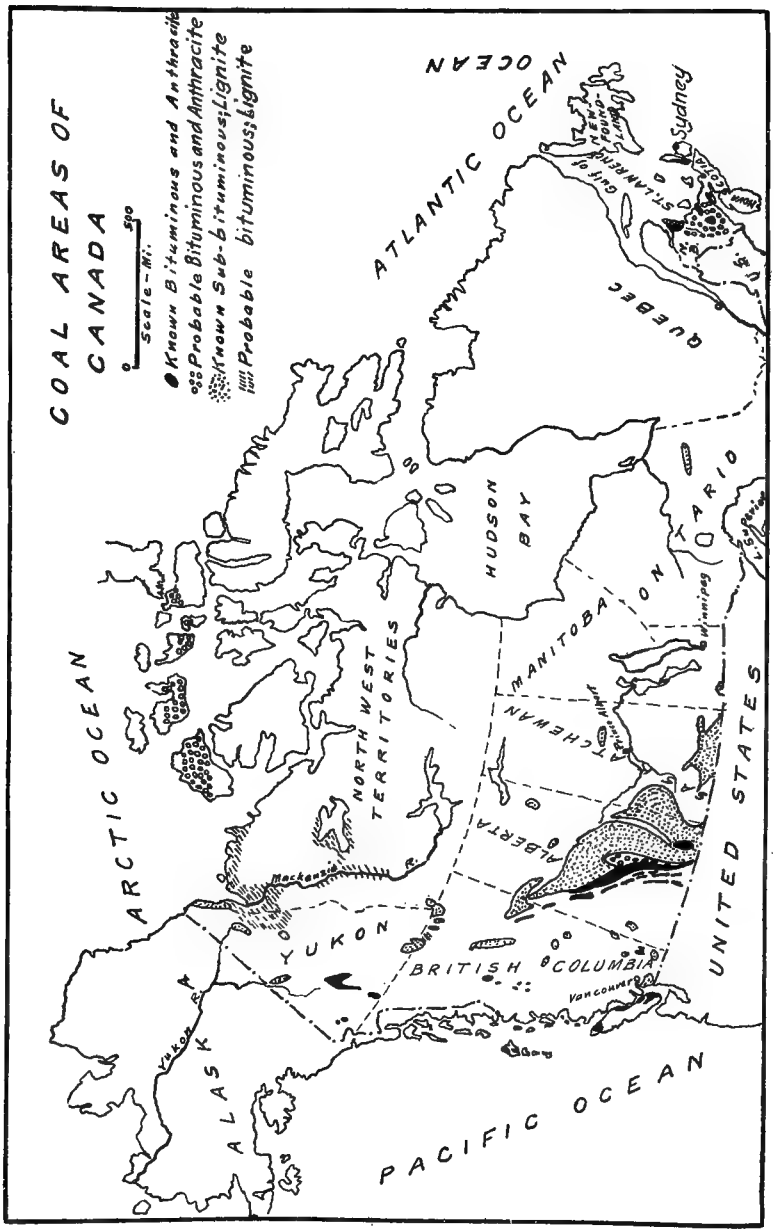


FIG. 57.—Outline map showing position of coal fields of Canada. (*After Dowling.*)

west shore of Cape Breton Island, coals from 2 to 12 feet thick are found. Coals are found also in Richmond County. In Pictou County, on the mainland, four beds are worked, one of them 38 feet thick. Carboniferous coals are mined also in Cumberland County, Nova Scotia.

In western Canada deposits of coal of Cretaceous and Tertiary age are widely distributed. The largest area is in southern Alberta, southwestern Saskatchewan, and southeastern British Columbia. In this area, in the Great Plains, Cretaceous coal beds lie nearly flat. The coals rank with lignites and sub-

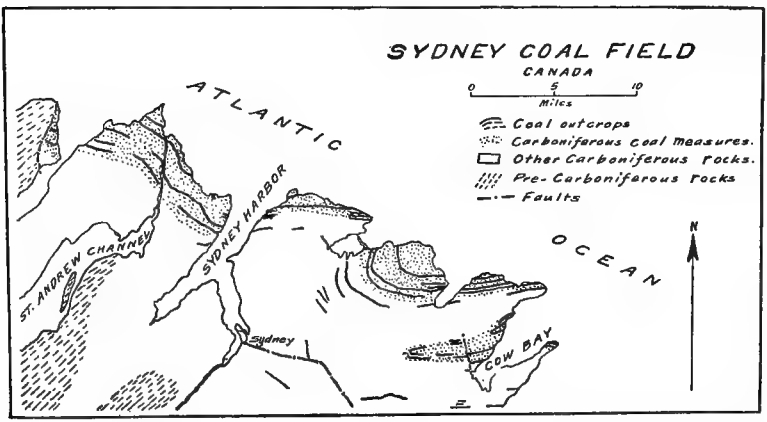


FIG. 58.—Sketch showing Sydney coal field Nova Scotia. (*After Dowling.*)

bituminous coal. Farther west, toward the mountains, the rock beds are folded and faulted and carry bituminous coal and anthracite.

In this part of Canada the principal developments are in the Crowsnest area and the Elk River area north of it (see Fig. 59). This region is famous for the number, thickness, and quality of its coal beds.[1]

The Crowsnest coal field is immediately west of the summit of the Rocky Mountains on the Crowsnest Pass. It is all included in British Columbia, except a small portion in the immediate vicinity of the pass, which crosses the watershed into Alberta. The area of Cretaceous rocks in the vicinity is nearly 500 square miles in extent. The coal measures, originally deposited over the

[1] DOWLING, D. B.: Coal Fields of British Columbia. Geol. Survey Canada *Mem.* 69, pp. 1–51, 1915.

whole of the area, have been eroded away around the edges, where the rocks are crumpled and folded, and along some of the deeper valleys so that the area of coal is only about 230 square miles.

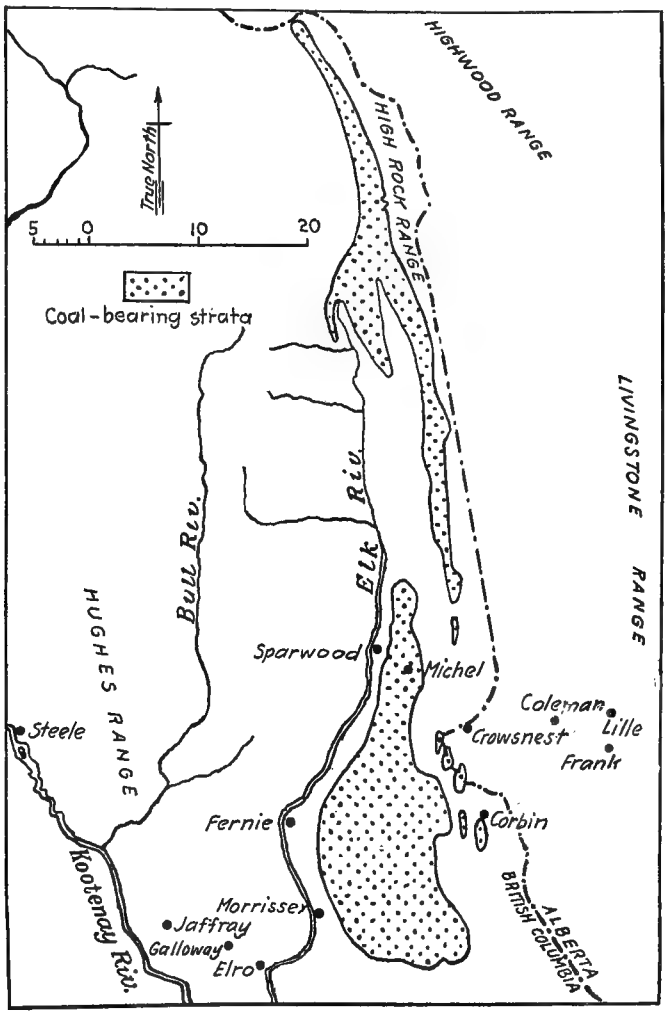


FIG. 59.—Sketch of Crowsnest coal-bearing area, British Columbia and Alberta. (*After McEvoy.*)

The Crowsnest field contains two beds that are 46 feet thick. McEvoy taking 100 feet as the workable thickness of the coals, estimated the amount of coal at over 22,000,000,000 tons. The

coal is mined in large quantities. Coke ovens are operated at three places.

AVERAGE OF 20 ANALYSES INCLUDING ALL SEAMS, CROWN MOUNTAIN CROWSNEST AREA

	PER CENT
Moisture	2.00
Volatile combustible	21.08
Fixed carbon	72.12
Ash	6.80
Heating value (British thermal units)	14,212

Bituminous coal is found in the Kootenay formation on Flathead River,[1] west of the Crowsnest area, in southern British Columbia. There are five seams, 4, 7, 8, 25, and 36 feet thick. The beds dip steeply; in places they are vertical.

Bituminous coal is mined from Cretaceous beds on Vancouver Island[2] and on the Queen Charlotte Islands.[3]

Newfoundland.—Carboniferous rocks containing coal underlie two large areas in western Newfoundland.[4] Some of the coal seams are 4½ feet thick. The analyses show good bituminous coal, low in ash. Although these coals are little developed, their character and location justify the prediction that coal mining will at some future date become an important industry in Newfoundland. The reserve probably is at least half a billion tons.

Mexico.—The principal coal field of Mexico is the Sabinas field of Coahuila,[5] not far from Eagle Pass and Laredo, Tex., and

[1] MACKENZIE, J. D.: Geology of a Portion of the Flathead Coal Area, British Columbia. Canada Geol. Survey *Mem.* 87, p. 11, 1916.

[2] CLAPP, C. H.: Southern Vancouver Island. Canada Geol. Survey; *Mem.* 13, pp. 1–208, 1912; Coal Fields of Vancouver Island. The *Coal Resources of the World.* vol. 2, pp. 509–513, 1913.

[3] CLAPP, C. H.: The Coal Fields of Queen Charlotte Island. *Coal Resources of the World,* vol. 2, pp. 513–515, 1913.

[4] HAWLEY, J. P.: The Coal Deposits of Newfoundland. *Coal Resources of the World,* vol. 2, pp. 431–438, 113.

[5] SALAZAR, L.: Mexican Railroads and the Mining Industry. Am. Inst. Min. Eng. *Trans.*, vol. 32, pp. 303–334, 1904.

KÜCHLER, JACOB: Valles de Sabinas y Salinas, *El Minero Mexico,* Sept. 12 and 19, 1901.

TUTTLE, E. G.: The Sabinas Coal Field. *Eng. and Min. Jour.*, vol. 58, pp. 390–392, 1894.

TUTTLE, E. G.: Arrangement of a Coal-washing Plant. School of Mines *Quart.*, vol. 17, pp. 378–400, 1896.

SCHMITZ, E. J.: Geological and Mineral Resources of the Rio Grande Region in Texas and Coahuila. Am. Inst. Min. Eng. *Trans.*, vol. 13, pp. 388–405, 1885.

about 70 miles south of the Rio Grande. The Coal is of late Cretaceous age, corresponding probably to the Laramie of the Rocky Mountain States.

The coal is found in two basins which are served by two branches of the Mexican National Railway.

Southwest of Sabinas, where the coal is mined, the beds dip at low angles. The principal bed has a bench 3 feet thick, above which are two thin layers separated from it by shale partings. The coal contains considerable shale. It is hand picked, and the fines are washed and converted to coke. The coal is low in moisture and high in ash (about 15 per cent.), and contains 60 to 66 per cent. of fixed carbon and 20 per cent. of volatile hydrocarbons. The coke is used at the lead and precious-metal smelters of Monterey.

Coal is found also in Sonora, in the Barranca or Santa Clara district, about 100 miles east of Hermosillo. The coal occurs in Triassic and Cretaceous rocks. The Triassic sediments are shales and sandstones, above which are igneous rocks. Much of the coal has been converted to anthracite and to natural coke by metamorphism due to igneous intrusions. Locally the coals are converted to graphite.[1]

Coals are known also near Zacualtipan, in the State of Hidalgo.[2]

In Oaxaca, west of the city of Oaxaca and south of the city of Puebla, sediments that consist mainly of shale and sandstone and that lie below a heavy Cretaceous limestone are steeply tilted and intruded by igneous rocks.[3] Included in the shale and sandstone series are many beds of coal from 4 to 7 feet thick. The coal contains about 20 per cent. of ash, about 74 per cent. of fixed carbon, and 5 per cent. of volatile matter. A small part of it is of higher grade.

Peat Deposits of the United States.—The origin of peat has been mentioned (p. 10). In some countries peat is used for fuel. Experiments have been made with peat powder under

[1] AGUILERA, J. G. and ORDINEZ, EZEQUIEL: Inst. Geol. Mexico *Bull.* Nos. 4, 5, and 6, 1897.

DUMBLE, E. T.: Triassic Coal and Coke in Sonora, Mexico. Geol. Soc. America Natural Coke of the Santa Clara Field, Mexico. Am. Inst. Min. Eng. *Trans.*, vol. 19, p. 546, 1899.

[2] COPE, E. D.: Am. Philos Soc. *Proc.*, No. 142, Oct. 16, 1885.

[3] BIRKINBINE, J. L. W.: Exploration of Certain Iron Ore and Coal Deposits of Oaxaca, Mexico. Am. Inst. Min. Eng. *Bull.* 45, pp. 671–693, 1910.

boilers, with results that are said to be satisfactory under certain conditions. In Ireland, Russia, and Sweden peat is cut in the summer and stacked in piles to dry for domestic use. Commonly the peat is dug by hand with a simple implement known as the slane. The peat is stacked above the level of the moisture of the bog and dries in the air. It shrinks and becomes coherent so that it may easily be handled. In some plants peat is recovered by machines.[1] It is macerated and spread into brick-like blocks that dry in the air. Experiments have shown that peat can be used also for making coke and gas. Oils, wood alcohol, and ammonia may be distilled from it. It is used also for fertilizer filler and for making paper and coarse fabrics. In Germany tanning compounds have been recovered from peat and used in the tanning industry. Although the amount of peat in the United States is very large, it has not been used to any appreciable extent for fuel. It contains 80 to 90 per cent. of water, and its recovery is difficult owing to the expense of handling so much water and removing it from the peat. The largest deposits are probably those of Minnesota,[2] about one-third of which is covered with peat. Large amounts are found also in Wisconsin, Michigan,[3] New Jersey,[4] New England,[5] and elsewhere.

[1] DAVIS, C. A.: The Use of Peat for Fuel and Other Purposes. U. S. Bureau of Mines *Bull.* 16, p. 8, 1911.

[2] SOPER, E. K.: The Peat Deposits of Minnesota. Minn. Geol. Survey *Bull.* 16, pp. 1–261, 1919.

[3] DAVIS, C. A.: Peat and Its Origin. Mich. Geol. Survey *Ann. Rept.* for 1906, pp. 95–361, 1907.

[4] PARMELEE, C. W., and MCCOURT, W. E.: Peat Deposits of Northern New Jersey. N. J. Geol. Survey *Ann. Rept.* for 1905, pp. 223–307.

[5] BASTIN, E. S., and DAVIS, C. A.: Peat Deposits of Maine. U. S. Geol. Survey *Bull.* 376, pp. 1–127, 1909.

CHAPTER IV

PETROLEUM AND NATURAL GAS

General Occurrence and Uses.—Petroleum (rock oil) is an inflammable mixture of oily hydrocarbons that exudes from the earth or is raised by pumping.

Asphaltum is a solid bitumen, and maltha a semifluid bitumen; both are residues formed by the partial evaporation of petroleum.

Natural gas is an aeriform mixture found at or beneath the surface of the earth and used for lighting, for fuel, and for generating power. It is commonly associated with petroleum.

Petroleum and natural gas are formed by the decomposition of plant and animal remains that have been buried with sediments in the sea. As a rule they accumulate in sands or sandstones associated with clays or shales or in porous limestones.

Salt water is generally associated with petroleum and is believed to be sea water that filled the pores of the sands when they were laid down in the sea.

Where folded rocks are saturated with petroleum, natural gas, and salt water, the oil is generally found above the water, and as a rule the gas is found above the oil. This rearrangement is due chiefly to gravity.

Crude petroleum is used extensively for fuel. It has a high evaporating power per unit of weight and is in demand for use under locomotive and marine boilers. Heavy oils are used for fuel more generally than lighter oils, because as a rule the heavy oil will not yield such valuable products. Heavy oils are used also for road dressing.

In refining petroleum, it is broken up by distillation into many products, including petroleum ether, gasoline, naphtha, kerosene, lubricating oils, vaseline, paraffin wax, and petroleum coke. Each of these materials has a variety of uses. Ether is used as a cooling agent and for priming internal-combustion engines in cold weather. Gasoline is used as fuel in internal-combustion engines, for cleaning cloth and other substances, and as a solvent of oil and grease. Naphtha is used for approximately the same purposes and much commercial gasoline is a mixture of gasoline and naphtha. Kerosene is used principally for illumination and

as a fuel for tractors. Lubricating oils are the heavy viscous products obtained by refining petroleum. Paraffin wax is used for making candles, for sealing, and as a preservative.

Many petroleum refineries do not produce all the products mentioned. Some "topping plants" distill off the lighter products, such as may be used as fuel for gasoline engines, and sell the heavier residues for fuel oil or for road dressing.

Asphalt is used for making pavements, roofings, and other building materials. Some oils on refining yield an artificial asphalt that is much like the natural product.

In order of total output of petroleum the countries rank (to 1918) as follows: United States, Russia, Mexico, Dutch East Indies, Galicia, Rumania, India, Japan, Canada, Peru, Germany, Trinidad, Egypt, Argentina, Italy. The world's principal oil fields are indicated on Figs. 60 and 61.

Oil or gas, or both, are found in strata ranging from the Cambrian to the Recent. Large amounts are found in the rocks formed during the Paleozoic, Mesozoic, and Cenozoic eras. Practically all the oil produced in Europe and in Asia is derived from the Mesozoic and Cenozoic formations, except a small production in Derbyshire, England, which comes from Paleozoic

AGE OF PRINCIPAL PETROLEUM RESERVOIRS IN THE UNITED STATES

	New York	Pennsylvania	West Virginia	Ohio	Kentucky	Tennessee	Indiana	Illinois	Missouri	Kansas	Oklahoma	Arkansas	Texas	Louisiana	Wyoming	California
Pleistocene	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	+
Pliocene	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	+
Miocene	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	+
Oligocene	..	..	..	..	..	..	..	..	..	..	..	..	+	+	[a] +	+
Eocene	..	..	..	..	..	..	..	..	..	..	..	..	+	+	..	+
Upper Cretaceous	..	..	..	..	..	..	..	..	..	..	..	..	+	+	+	+
Lower Cretaceous	..	..	..	..	..	..	..	..	..	..	+					
Jurassic	..	..	..	..	..	..	..	..	..	..	..	..	..	..	+	
Triassic	..	..	..	..	..	..	..	..	..	..	..	..	..	..	+	
Permian	..	..	..	..	..	..	..	..	..	..	+	..	+	..	[b] +	
Pennsylvanian	..	+	+	+	+	..	+	+	+	+	+	gas	+			
Mississippian	..	+	+	+	+	+	+	+	..	..	+	..	+			
Devonian	+	+	+	+	+	+	+									
Silurian	gas	..	..	+	+	+	+	+								
Ordovician	gas	..	..	+	+	+	+	+								
Cambrian	gas															

[a] A little oil is found in the White River formation (Oligocene) in the Douglas field.
[b] Embar formation, partly Pennsylvanian.

AGE OF PRINCIPAL PETROLEUM RESERVOIRS IN THE CARIBBEAN REGION AND SOUTH AMERICA

	Mexico	Cuba	Haiti	Barbados	Trinidad	Venezuela	Caribbean Colombia	Magdalena and Santander, Colombia	Peru and Ecuador	Argentina and Bolivia
Pleistocene										
Pliocene	..	..	..	..	+					
Miocene	..	..	..	+	+					
Oligocene	..	..	..	..	..	..	+	+		
Eocene	+	..	..	..	..	..	..	..	+	
Cretaceous	+	..	+?	..	..	+	..	+	..	+
Jurassic	..	+?								

beds. In the Eurasian fields the Miocene and Oligocene are the most productive strata, although the Eocene yields considerable oil in Galicia. In Mexico, Venezuela, and Argentina the principal producing strata are Cretaceous. In Colombia oil is derived from the Cretaceous and the Eocene. The production of Barbados and most of that of Trinidad is derived from Miocene strata. In North America large amounts of petroleum are found in strata of Paleozoic, Mesozoic, and Cenozoic age.

Indications of Oil and Associated Materials.—Oil springs are found in many oil fields. The oil exudes at the outcrops of oil-bearing strata and from fissures that connect with oil reservoirs. Asphaltites, which result from the drying of oil, are found in similar positions. Bituminous dikes are found where oil dries out in fissures. Not all oil pools are marked by oil seeps or asphalts, but most large fields have seeps at one place or another, or outcropping sands that will commonly show on testing[1] a little oil or asphaltite. (Figs. 62 and 63.) On the other hand, seeps are shown at many places where tests have failed to reveal commercial oil deposits.

Because salt water is generally associated with oil, salt springs are regarded favorably in some localities, but there are many salt springs that are not associated with oil. Sulphur and its compounds are generally present in oil, and on oxidizing they yield sulphuric acid. This acid is at places therefore regarded as an indication of oil, but acid waters are common outside of oil

[1] The sample is ground and shaken with carbon tetrachloride and filtered. The filtrate is slowly evaporated on a white plate. Any oil present will form a solid residue, which is clearly shown on the white porcelain.

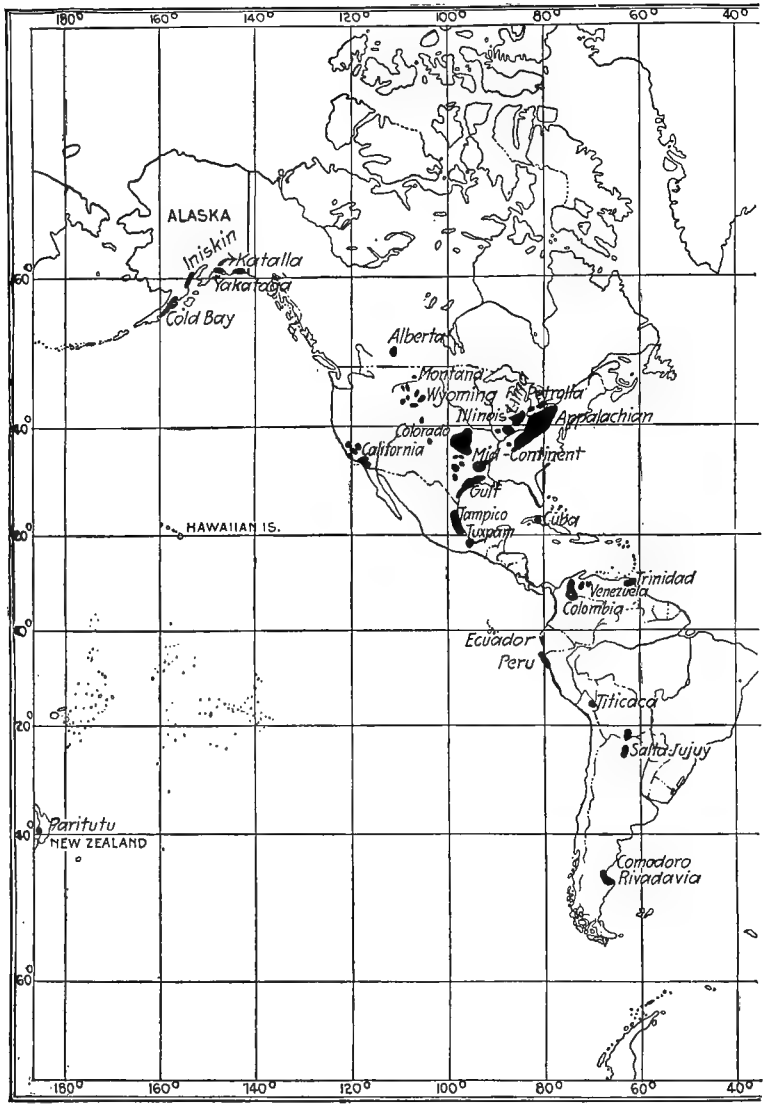


FIG. 60.—Map showing producing oil fields of Western Hemisphere (a few prospective fields are shown).

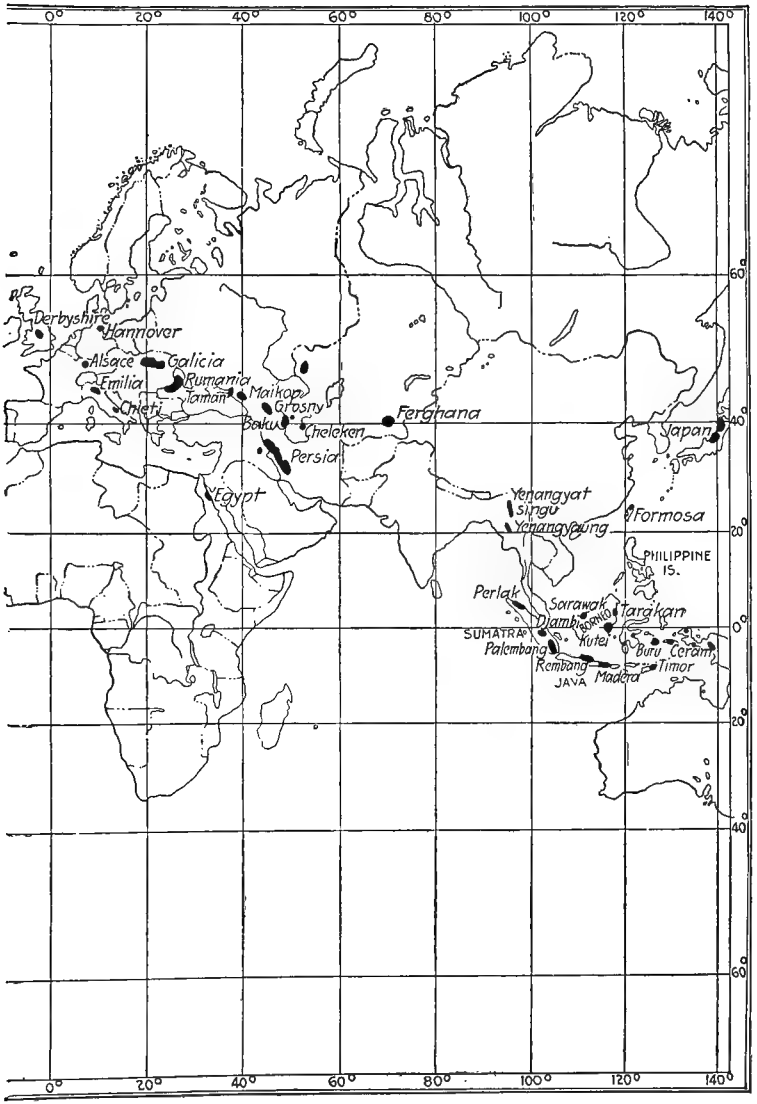


FIG. 61.—Map showing producing oil fields of Eastern Hemisphere (a few prospective fields are shown).

fields. Gas is nearly everywhere associated with oil, and the discovery of gas seeps has led to the drilling of oil fields. Marsh gas is formed, however, in peat bogs or from coal that is undergoing decomposition, and it is not to be regarded as a certain evidence of oil. Nitrogen, carbon dioxide, and carbon monoxide have little significance. Sulphur gases (SO_2, SO_3, H_2S) are commonly associated with oil deposits, but they are found also at many places far removed from oil fields. In general the gas

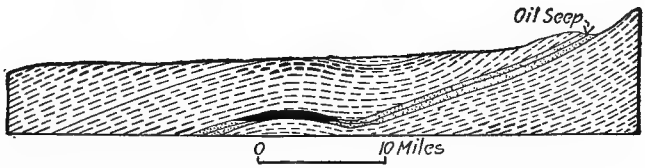


FIG. 62.—Sketch showing oil seeps at outcrop of petroliferous stratum and an accumulation of oil and gas (black) many miles down the dip from the outcrop.

that is regarded as most significant is one that contains some hydrocarbons heavier than marsh gas, especially the "gasoline vapors," which on condensation of the gas yield gasoline. "Paraffin dirt," which is found in some fields, is regarded as evidence of gas seeps. It is a colloidal material consisting of clay and silica. Much of it, at least, contains no paraffin.[1] Mud volcanoes are formed where gas blows off a mud covering that has sealed its vent. Mud dikes are found above oil accumulations

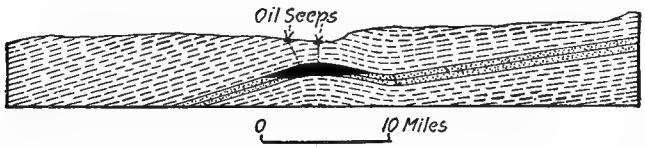


FIG. 63.—Sketch showing oil seeps at crest of fold above oil accumulation (black).

in some fields. They are abundant in Burma, where they are commonly regarded as fillings of the vents through which gas once issued.

Oil is believed to be derived largely from organic material that has been buried in clay strata. Organic clays or muds, on solidifying, become oil shales. Oil shales are found in many oil fields and are looked upon as favorable indications, but they

[1] BROKAW, A. D.: Interpretation of the So-called Paraffin Dirt of the Gulf Coast Oil Fields. Am Inst. Min. Eng. *Trans.* 61, pp. 482–500, 1919.

occur also in many regions in which no commercial deposits of oil are known. Oil shales in some regions are burned to considerable depths by the oxidation of the organic matter they contain.

All superficial evidences are, of course, to be weighed in connection with their setting—that is, the character and distribution of the underlying rocks and their attitude and structure.

Association of Salt Water with Oil.—In nearly all the large oil-producing regions of the world salt water is associated with the oil. It is believed to be the sea water that was buried with the strata that contained organic material which on decomposition, became oil. In the Grass Creek anticline and in part of the Salt Creek field, Wyoming, the oil is associated with water that is only slightly salt or feebly alkaline. The original water of the sediments has evidently been diluted or driven out by

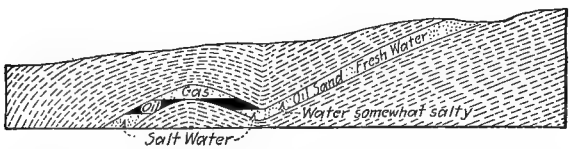


FIG. 64.—Sketch showing a common relationship of oil, gas, salt water, water somewhat salty, and fresh water. The circulation of fresh ground water sweeps out the brine near the surface and dilutes it in depth.

fresh ground water (Fig. 64). In the Sunset-Midway field, California,[1] chlorides increase from the surface downward and sulphates decrease. Near the oil deposits sulphates have been almost eliminated.

Reservoir Rocks.—The rocks that contain oil and gas are sands, sandstones, marls, limestones, and dolomites. Oil and gas are found also in fissures in igneous and sedimentary rocks, but such accumulations are less common. Many sandstones contain as much as 20 per cent. of pore space, and some contain even more. Much oil is found in sands of very fine grain. The sands from some fields will all pass through sieves having 100 meshes to the inch. Clay mixed with sand greatly decreases porosity, and much clay will stop accumulation. The producing sands range in thickness from a few feet to 50 feet or more and are rarely as much as 100 feet thick. The thicker sands, however,

[1] ROGERS, G. S.: Chemical Relations of the Oil-field Waters in San Joaquin Valley, California. U. S. Geol. Survey *Bull.* 653, p. 113, 1917.

generally contain clay partings. As a rule sands are more or less spotted with hard or impervious portions. Few sands are equally productive in all parts of a field. The sands are composed of quartz, feldspar, magnetite, ilmenite and other minerals. Ferromagnesian minerals, such as hornblende and olivine, on weathering yield clay, which is unfavorable to accumulation. In recent years microscopic study of sands has been undertaken to identify and correlate the strata of a region.

Calcareous rocks that contain oil are commonly dolomitic. The dolomitization of limestone according to Orton,[1] results in the production of much pore space. Formerly it was supposed by many that only dolomites form highly productive reservoirs, but recently oil has been reported in limestone that is only slightly dolomitic.

Oil-bearing strata in all the important fields of the world are covered by clayey rocks, either clays, shales, or clayey marls. These rocks, being impermeable to fluids, seal the reservoirs. In some fields oil is found below 100 feet or less of impermeable rock. Flowing wells have been brought in at depths of less than 100 feet. In general, however, the impermeable coverings are thicker. The field in Lambton County, Ontario, at depths between 350 and 400 feet yielded large flowing wells, producing 3,000 to 6,000 barrels a day and spouting high in the air. The wells now producing most of the oil in North America are from 1,000 to 4,000 feet deep.

Some Properties of Petroleum.—Most crude oils are opaque except in very thin layers. As a rule the color is brown to black, though some are red and others yellow. At a few places white oil or oil of pale lemon-yellow color is found. Most crude oils as seen by reflected light, have a greenish cast.

Oils of different fields have characteristic odors. Pennsylvania oils smell like gasoline; California oils smell like coal tar, and Lima-Indiana oils have the disagreeable ordor of sulphur compounds.

Oils differ greatly in gravity, although few are as heavy as water. The lighter oils are generally more valuable than the heavy oils because they will yield more gasoline and kerosene. Frequently oil is sold by weight. The specific gravity of oil is its weight

[1] Orton, E.: The Trenton Limestone as a Source of Petroleum and Natural Gas in Ohio and Indiana. U. S. Geol. Survey *Eighth Ann. Rept.*, part 2, p. 583, 1889.

compared with that of distilled water taken as 1,000. Oil that is as heavy as water generally contains mineral matter in suspension. In the United States the Baumé scale is used almost exclusively. On this scale the weight of water is arbitrarily placed at 10° and the degrees increase as the weight of the liquid decreases. The following formula[1] is used for converting gravity into Baumé scale from the decimal standard:

$$°\text{Baumé} = \frac{140}{\text{specific gravity of liquid}} - 130$$

In general, the specific gravity is taken by placing a hydrometer in the oil and reading directly off the scale.

The viscosity of oil varies with its specific gravity. It is measured by ascertaining the time it takes a given amount of oil to flow through a small opening. Viscosity decreases with increased temperature. Some oils are heated to facilitate their movement through pipe lines. The lubricating properties of oil are closely related to its viscosity.

Chemically petroleums are mixtures of compounds of carbon and hydrogen, generally with impurities consisting of sulphur and nitrogen compounds. Oils are commonly classified as those with asphaltic base and those with paraffin base. Asphaltic oils yield on distillation a dark-colored asphaltic residue. Paraffin oils yeild on distillation lighter-colored paraffins. Asphaltic oils generally sell at lower prices than paraffin oils. Many oils yield both asphalt and paraffin.

Composition of Natural Gas.—Natural gas is associated with practically all petroleum. It rises to higher points of reservoirs and is absorbed in the oil. It is generally under considerable pressure. It is the pressure of the gas that causes the wells to spout and that forces the oil to wells that are pumped. Inflammable gas is found at many places, however, where no oil is present. It rises from marshes and swamps. Analyses of inflammable gas show that it generally consists mainly of methane (CH_4). Some gases contain also ethane (C_2H_6), carbon dioxide (CO_2), and nitrogen. Small amounts of helium, hydrogen sulphide (H_2S), carbon monoxide (CO), olefines, and other compounds are commonly present.

Much gasoline[2] is recovered from natural gas. By one method

[1] Used only for fluids as light as water or lighter.

[2] Largely pentane and hexane.

the gas is condensed, and the gasoline vapors become liquid and are drawn off. By another method the gas is passed through heavy oil, which absorbs the gasoline vapors. The gasoline is subsequently recovered from the oil by distillation. Some gasoline is recovered also from drips in pipe lines that carry gas.

Origin of Petroleum and Gas.—There are two groups of theories regarding the origin of oil and gas—the inorganic theories and the organic theories. The inorganic theories assume that water or gases within the earth, acting on certain chemical compounds, generate hydrocarbons, which accumulate at certain places. Carbon dioxide at high temperature can react on alkali metals, which some have supposed that the interior of the earth contains, and yield acetylene, which would break down, forming higher hydrocarbons.[1] Acetylene heated to high temperatures yields benzene. Mendelief suggested that iron carbides are present in the interior of the earth, and that water coming in contact with them yields hydrocarbons. These theories, which are allied closely with the igneous theories of the origin of oil, have not found much support, because most of the great oil fields are remote from centers of volcanism.

The theory that oil is generated by distillation of organic matter buried in sediments was suggested by Newberry[2] and by Orton.[3] Experiments have shown that hydrocarbons like those present in petroleum may be obtained by distillation of fish remains or of vegetable remains, or of mixtures of them.

A theory that is accepted by many investigators today is that there are two stages[4] in the formation of petroleum from organic material. In one biochemical processes predominate; in the other geochemical or dynamo-chemical processes. The organic matter was deposited on the sea bottom in estuaries or not far

[1] Berthelot, P. E. M.: Sur l'Origine des Carbures et des Combustibles mineraux. Compt. Rend., vol. 62, pp. 949–951, 1866.

[2] Newberry, J. S.: Devonian System. Ohio Geol. Survey, vol. 1, p. 160, 1873.

[3] Orton, Edward: The Origin and Accumulation of Petroleum and Natural Gas. Ohio Geol. Survey, vol. 6, p. 74, 1888.

[4] Dalton, W. H.: On the Origin of Petroleum. Econ. Geology, vol. 4, pp. 603–631, 1909.

White, David: Some Relations in Origin Between Coal and Petroleum. Washington Acad. Sci. *Jour.*, vol. 5, pp. 189–212, 1915. Late Theories Regarding the Origin of Oil. Geol. Soc. America *Bull.*, vol. 28, pp. 727–734, 1917.

from shore and in lakes. Through the action of anaerobic bacteria it is changed, the cellulose probably being altered to other compounds and the waxes and fats set free. That plants of low orders when distilled, can yield petroleum was demonstrated by Renault.[1]

Because practically all important accumulations of oil are in or closely associated with marine strata, it is supposed that salt water is necessary for their genesis. Some oil shales, however, contain remains of fresh-water animals, and such shales contain "kerogen" or the solid, partly altered organic matter that is believed by many to be the principal source of petroleum.

In California, as shown by Arnold, Anderson, Johnson, and their associates, the oil accumulations are associated with great bodies of marine diatomaceous sediments. Diatoms are vegetable organisms containing material that can be broken down into oily substances.

Accumulation of Oil and Gas.—In folded strata that are saturated with water, oil and gas, the oil tends to rise above the water, and the gas above the oil. If the rock contains no water the oil tends to accumulate in synclines. If some water is present, the oil floats on the water and will be found lower on the folds. The theory of arrangement according to density is termed the anticlinal theory.[2] It was first proposed to account for the distribution of oil, gas and water in the Burning Springs-Volcano anticline and in the Petrolia field, Lambton County, Ontario. In most of the pools in the Appalachian fields, however, the oil-bearing rocks are not saturated and the oil is not conspicuously related to anticlinal crests. As this field was developed many investigators lost confidence in the theory. Later, however, as the fields of Lima-Indiana, Illinois, Oklahoma, Kansas, Texas, Louisiana Wyoming, and California were developed the theory gained ground, because in nearly all these fields the oil is found either

[1] RENAULT, B.: Houille et Bactériaces. Soc. Hist. Nat. Autun. *Bull.*, vol. 9, pp. 475–500, 1896; Compt. Rend., vol. 117, p. 593, 1893.

[2] ANDREWS, E. B.: Rock Oil, Its Geological Relations and Distribution. Am. Jour. Sci., *Second series*, vol. 32, pp. 85–93, 1861.

HUNT, T. S.: Notes on the Geology of Petroleum or Rock Oil. *Canadian Naturalist*, vol. 6, pp. 241–255, 1864.

WINCHELL, A.: On the Oil Formation in Michigan and Elsewhere. Am. Jour. Sci., *Second series*, vol. 39, p. 352, 1865.

WHITE, I. C.: The Geology of Natural Gas. *Science*, vol. 6, June 26, 1885.

near crests of anticlines, on structural terraces, or on sealed monoclines. The theory, with modifications,[1] has now been firmly established.

Various theories have been proposed as corollaries to the anticlinal theory. Of these the hydromotive theory of Munn is perhaps the best known.[2] He suggests that bodies of water in motion carry the oil with them. If the water moved downward or laterally, it could carry the oil with it, and the oil carried down would tend to float into any higher structural features it encountered and accumulate in them. The higher folds would serve as oil traps raised above the passageways of water and oil.

Johnson[3] suggests that the oil is carried through the sands as films on globules of gas. Daly[4] appeals to pressures generated as a result of diastrophic movement. These methods of segregation probably assist gravitational separation to some extent.

A series of experiments has recently been made, in which gas was introduced into an oil-soaked sand in a closed system. Tubes about six feet long, were bent to form anticlines of which the limbs had slopes of about 15°(Fig. 65*a*). These were filled with sand which had been mixed with oil. The amount of oil introduced was only that which adhered to the sand, the excess having been drained away. This was charged, together with sea water which had been made slightly acid with acetic acid. The tube was completely filled with the mixture and allowed to remain a considerable period, as shown by Fig. 65*b*. No segregation took place except locally, where the oil gathered into small drops. Subsequently small amounts of dolomitic limestone were introduced at each end of the tube (Fig. 65*b*; *A'*, *A'*). After 48 hours a considerable segregation of oil, gas, and water had taken place (Fig. 65*c*). The gas occupied the highest part of the tube (*D*), and rested on oil (*C*, *C'*), which in turn rested on salt water (*B*, *B'*).[5] The space occupied by the gas represents air

[1] The theory of gravitational separation as applied in the broadest sense has been termed by Clapp the "structural theory."

[2] MUNN, M. J.: The Anticlinal and Hydraulic Theories of Oil Accumulation, *Econ. Geol.*, vol. 4, pp. 509–529, 1909.

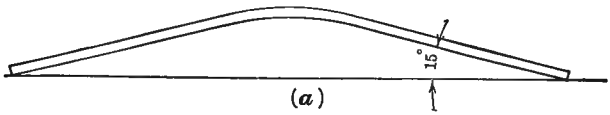
[3] JOHNSON, R. W.: The Accumulation of Oil and Gas in Sandstone. *Science*, new ser., vol. 35, pp. 458–459, 1912.

[4] DALY, MARCEL: Water Surfaces in the Oil Fields. Am. Inst. Min. Eng. *Trans.*, vol. 59, 557–563, 1918.

[5] THIEL, G. A.: Gas an Important Factor in Oil Occurrence. Eng. and Min. *Jour.*, vol. 109, p. 888, 1920.

spaces which it was not possible to eliminate in charging the water and the oil-soaked sand in the tube, together with the space made available by the gas pressure forcing liquids into small cracks of the sand.

The method of segregation is due principally to gravity. Gravity, however, will not operate in the absence of gas, because adhesion is great enough to hold the oil tightly to the sand. The gas generated presses on both oil and water, but the oil being lighter is pushed up farther and rides above the water. It is clear that the oil is not carried by the gas as films on gas bubbles, because the amount of oil is much greater than would be required



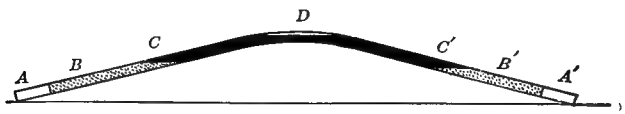
(*a*)

Glass tube bent to represent anticline.



(*b*)

Glass tube filled with oil sand and sea water, acidified with acetic acid. Ground dolomite was introduced at *A* and *A′*.



(*c*)

Same as (*b*) after 48 hours.

AA′ is dolomite; *BB′* sea water in sand; *CC′* segregation of oil in sand; *D*, accumulation of gas in sand.

FIG. 65.—Illustrations of experiment showing accumulation of oil in sand. The system is closed and contains gas under pressure.

to form films. A small amount of gas seems to be as effective as a large amount, provided the pressure is sufficient. That the pressure is effective, rather than the movement of the gas, is clear from other experiments. The system, with acid and dolomite, was set up exactly as is shown in Fig. 65*c*, but the tube was arranged to represent a syncline rather than an anticline. The gas rose on either limb, near the end of the tube, the oil below the gas, and water segregated below the oil. A terrace was set up (Fig. 66), the tube being bent so that two arms sloped

approximately 15°. Between the two arms the tube was level, as it was also at the upper end. After being charged with oil-soaked sand, acidified sea water, and dolomite, the oil rose to the first level of the terrace and remained several days. Subsequently it moved up from the higher inclined arm to the flat portion of the tube. There was a strong tendency for the maximum accumulation to remain in the flat part of the tube nearest the bent limb. Similar results were obtained by using ether and warming the system instead of introducing acid and dolomite to generate gas.

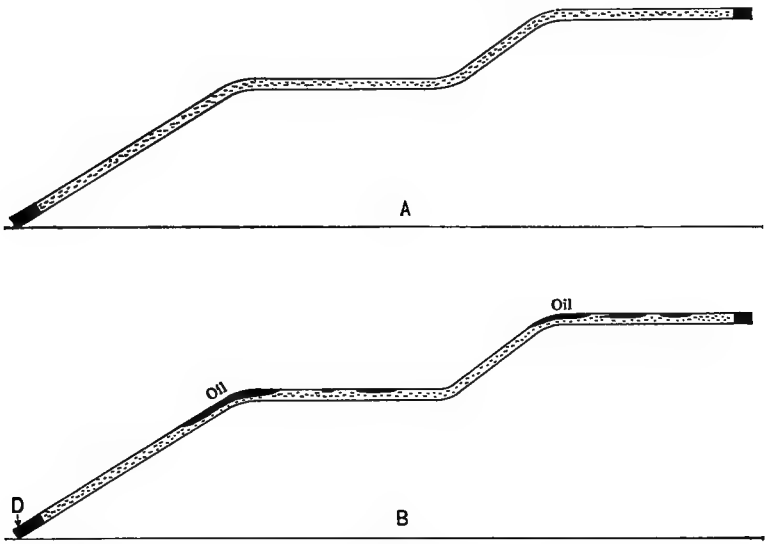


FIG. 66.—Experiment illustrating accumulation of oil on terraces. *A*, Clean sand saturated with oil charged with acidified water in tube. *B*, Clean sand saturated with oil, charged with acidified water in tube. Dolomite, introduced at *D*, generated gas which caused the oil to segregate near bends and at flat parts of tube. Ultimately most of the oil rose to higher terrace.

As a result of surface tension water and oil are drawn into small capillary openings regardless of the force of gravity. Examples are the movement of water in a sponge or the rise of oil in a lamp wick. As water has about three times the surface tension of oil[1] under conditions that exist in rocks, there is a tendency for water to be drawn into the finest of openings, displacing oil and gas in them. If water-soaked sand and oil-

[1] WASHBURNE, C. W.: The Capillary Concentration of Oil and Gas. Am. Inst. Min. Eng. *Trans.*, vol. 50, pp. 829–842, 1914.

soaked mud are placed in contact the water will be drawn into the mud and the oil will displace water in the sand.[1] In some fields[2] there is a noteworthy tendency for oil and water to occupy the sands that have the largest openings.

Classification of Oil and Gas Reservoirs

A. Elevated structural features.
   1. Anticlines and domes: Appalachian fields and Lima-Indiana (in part), southwestern Ontario, Illinois, Mid-Continent field; Wyoming, California, Gulf coast; Mexico (domes near intrusives); Trinidad; Colombia, Galicia; Rumania; Baku, Grozny, Sviatoi, and Cheleken, Russia; Burma; Oceanica; Japan.
   2. Monoclines sealed by
      (*a*) Overlying and underlying shales, joining above reservoirs: Appalachian fields, in Pennsylvania, West Virginia, and Ohio, in part; some Mid-Continent fields.
      (*b*) Faulting: Los Angeles, California; Benigadi, Russia; Rumania and Galicia in part.
      (*c*) Local cementation of reservoir rock: Glenn pool, Oklahoma; probably many others.
      (*d*) Asphalt: Coalinga and McKittrick-Midway-Sunset fields, California in part.
      (*e*) Unconformities: Maikop, Russia; Douglas, Wyoming.
      (*f*) Igneous intrusions: Tuxpam-Tampico field, Vera Cruz, Mexico.

B. Flat-lying beds.
   1. Aclines involving oil sands: possibly part of Comodoro Rivadavia, Argentina.
   2. Terraces: Pennsylvania, Ohio-Indiana, districts in eastern part of Kansas-Oklahoma field in part.

C. Depressed structural features.
   1. Synclines and basins: Catskill sands in Pennsylvania and West Virginia; some parts of fields of California and Galicia; unimportant districts of Rocky Mountain fields.

D. Fissures.
   1. In shales: Florence, Colorado; part of Salt Creek, Wyoming; part of Cleveland, Ohio.
   2. In schists: Small part of Santa Clara, California.
   3. In igneous rocks: Cuba part of Furbero, Mexico.

E. Combinations of two or more structural features named above: Numerous fields.

[1] McCoy, A. W.: Notes on Principles of Oil Accumulation. *Jour. Geol.*, vol. 27, pp. 252-262, 1919.

[2] Munn, M. J.: Studies in the Anticlinal Theory of Oil and Gas Accumulation. *Econ. Geol.*, vol. 4, pp. 141–157, 1909.

SALIENT FEATURES OF CERTAIN OIL FIELDS

Field	Reservoir rocks		Cover	Principal structural features	Surface indications of oil
	Age	Kind[a]			
Appalachian	Pennsylvanian to Devonian	Sandstone and limestone	Shale	Anticlines, terraces, and dry synclines	Oil and gas seeps, grahamite
Ohio-Indiana	Ordovician	Porous dolomite	Shale	Half domes and terraces on Cincinnati anticline, domes	Gas seeps at Findlay, Ohio
Illinois	Pennsylvanian and Mississippian, Ordovician	Sandstone and porous oolitic limestone	Shale	La Salle anticline and minor flexures	Oil seeps rare or lacking
Northeast Oklahoma and Kansas	Pennsylvanian[b]	Sandstone, limestone	Shale	Anticlines, domes, half domes, and terraces	Asphalt to east, where oil-bearing strata crop out
North Central Texas	Pennsylvanian and Mississippian	Sandstone	Shale	Arched monocline	Rare
Gulf Coast (salines)	Miocene and Eocene; some in Cretaceous	Porous dolomitic limestone and sandstone	Clay or shale	Domes	Mounds, acid waters, salt water, sulphur, gas, "paraffin dirt"
Sabine, Louisiana and Texas	Upper Cretaceous	Sandstone, limestone	Clay	Domes	Gas seeps, etc.
Rocky Mountains, (Wyoming-Colorado)	Cretaceous and Carboniferous	Sandstone	Shale	Domes are typical; fracture zone at Florence, Colorado; fault traps	Some tar springs and gas seeps
California	Late Tertiary, mainly Miocene to Cretaceous	Sandstone	Shale and clay	Anticlines, domes, plunging anticlines, overturns, monoclines, fault zones, fault traps, etc.	Asphalt, brea, tar springs, etc.

[a] Rocks designated sandstone in tables, include also sands.

[b] Recently some oil has been found in Mississippian and Permian.

SALIENT FEATURES OF CERTAIN OIL FIELDS—*Concluded*

Field	Reservoir rocks		Cover	Principal structural features	Surface indications of oil
	Age	Kind[a]			
Tampico, Mexico	Basal Tertiary and Cretaceous	Limestone and sands	Shale	Anticlines, domes, and disturbances near igneous rocks	Oil seeps, asphaltum
Trinidad	Tertiary	Sandstone	Clay	Anticlines	Asphalt, oil, and gas seeps
Venezuela	Tertiary and Cretaceous	Sandstone	Clay shale	Anticlines	Asphalt, oil seeps
Colombia	Tertiary and Cretaceous	Sandstone	Clay shale	Anticlines	Asphalt, mud volcanoes, oil seeps
Rivadavia, Argentina	Upper Cretaceous	Sandstone, coarse, pebbly	Shale	Flat, minor warpings	None
Lower Alsace	Oligocene	Sandstone	Marl	Faulted monoclines	Pitch springs, asphalt
Boryslaw, Galicia	Miocene and Oligocene	Sandstone	Clay and shale	Anticlines, synclines	Oil seeps, ozokerite
Schodnica, Galicia	Eocene, Cretaceous	Sandstone, conglomerate	Clay and shale	Anticlines, synclines	Oil seeps
Rumania	Pliocene, Miocene, and Oligocene	Sandstone, conglomerates	Clays, shales	Anticlines, fault traps	Mud volcanoes, oil seeps, gas seeps
Baku, Russia	Miocene and Oligocene	Sandstone	Clays, marls	Anticlines, monoclines	Oil seeps, mud volcanoes, gas seeps
Grozny, Russia	Miocene	Sandstone	Clays, shales	Anticlines	Oil seeps, gas seeps
Maikop, Russia	Oligocene	Sandstone	Shale	Unconformity	Oil seeps, asphalt
Egypt	Miocene and Cretaceous	Sandstone, limestone	Clay and shale	Anticlines in part	Oil seeps, asphalt
Burma	Miocene	Sandstone	Clay	Anticlines	Oil seeps, gas seeps
Sumatra	Miocene	Sandstone	Clays, shales	Anticlines	Oil seeps, mud volcanoes
Java	Miocene	Sandstone	Clay marls	Anticlines	Oil seeps, etc.
Japan	Tertiary	Sandstone and tuffs	Shale	Anticlines	Oil seeps, etc.

[a] Rocks designated sandstone in tables, includes also sands.

It is believed that certain light-colored, light-weight oils have formed by the fractionation of petroleum that has passed through clay. When oil is mixed with fine clay (fuller's earth) it loses some of its heavier constituents.[1] When crude oil is

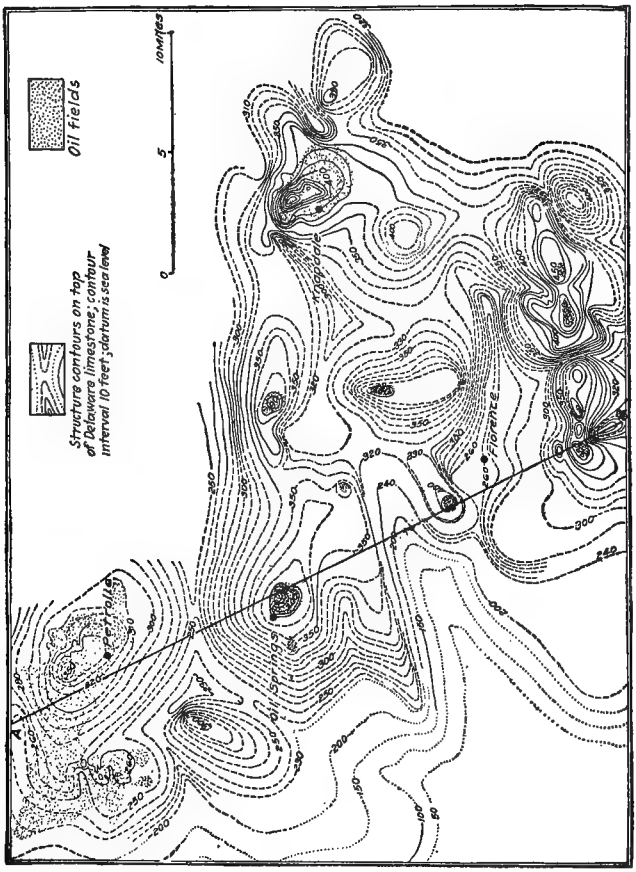


FIG. 67.—Sketch showing structure of principal oil region of Lambton County, Ontario. (*After Williams.*)

allowed to rise through a tube packed with fuller's earth, the fraction at the top of the tube is lighter than the one at the bottom. The paraffin compounds tend to accumulate at the top of the tube, and the unsaturated hydrocarbons at the bottom.

[1] DAY, D. T.: Experiments in the Diffusion of Crude Petroleum through Fuller's Earth. *Science*, new ser., vol. 17, pp. 1007–1008, 1903.

Oil and Gas Reservoirs.—Many oil and gas reservoirs are on anticlines and domes (Figs. 67–69). The domes are generally elongated, and most of them have been formed by earth movements. This is suggested by the positions of their longer axes, many of which are parallel to neighboring mountain folds. It is believed by some, however, that certain folds have been formed by the compacting and settling of sediments that were deposited upon cores, ridges, or other bodies of compact rocks (p. 157). The material on the sides of the cores, being thicker, has been compacted more and the rocks have sagged down, dipping away from the cores. In the Tampico-Tuxpam field of Mexico igneous intrusions have caused gentle doming sufficient to influence accumulation. Domes with cores of salt yield oil in the Gulf coast field of the United States and in Rumania. Some oil-bearing anticlines are very low; others have steep dips (Figs. 70–74).

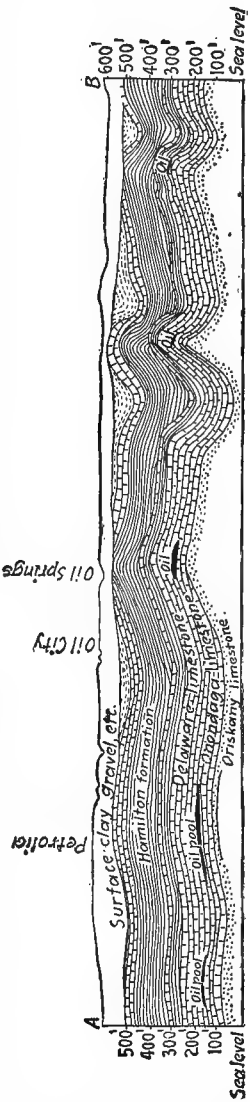


FIG. 68.—Cross-section of Petrolia and Oil Springs oil fields, Lambton County, Ontario, along line *AB* in Fig. 67. Vertical scale is much exaggerated. (*Redrawn from a section by Williams.*)

In some fields domes are superimposed on longer anticlines and are arranged in lines parallel to greater mountain folds. In the Big Horn Basin, Wyoming, there are two circles of domes. Only the one on the inner side, toward the center of the basin has shown much production. In many other fields also the lower domes, or those on the basinward side of the folded areas, are generally more productive than those on the mountainward side (Fig. 75). There is a tendency also for the maximum accumulation in pools to occupy the gentler flank of a fold, which is generally toward the basin, in the direction in which the greatest gathering ground lies.

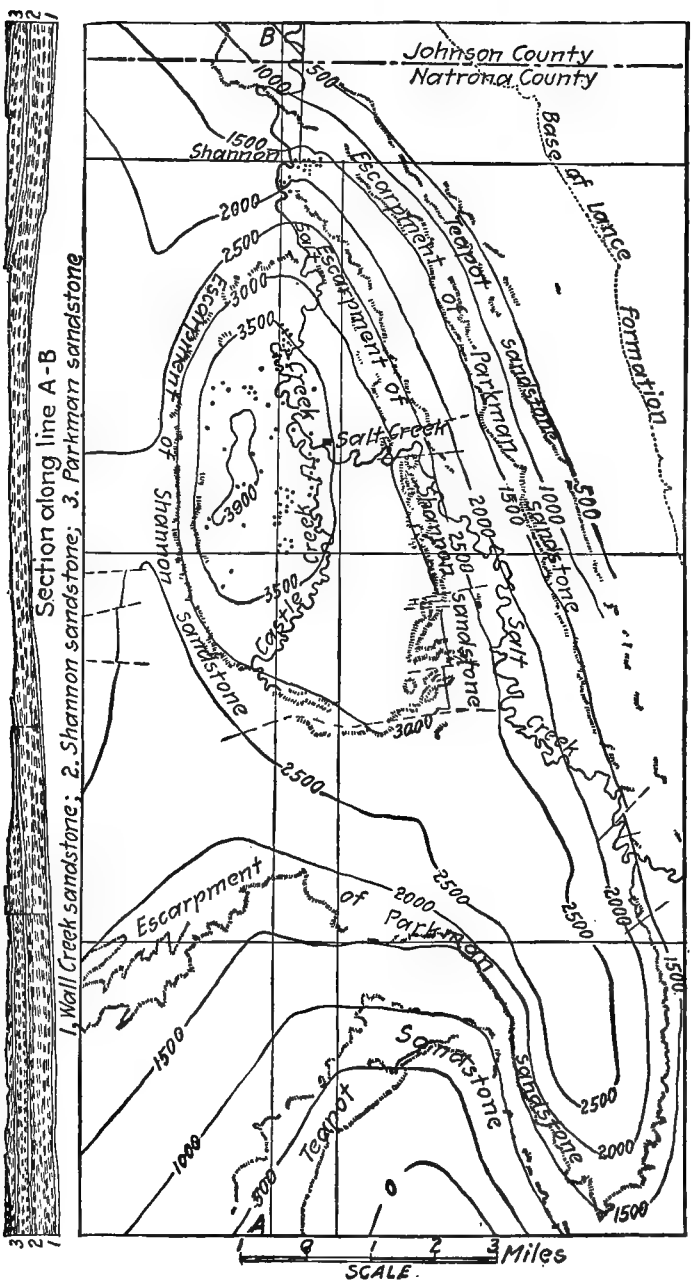


FIG. 69.—Structure map of the Salt Creek oil field, including the Shannon Pool and Teapot dome, Natrona County, Wyoming. Structure contours show elevations of Wall Creek sandstone above sea level. (*After Wegeman.*)



FIG. 70.—Section of Dropright dome, Cushing field, Oklahoma. Vertical and horizontal scale are the same. Shows curvature of Pawhuska limestone from northwest corner of section 5 to northwest corner of section 27, T. 8, N., R. 7, E. (*Data from Beal.*)

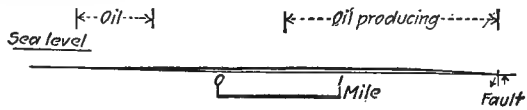


FIG. 71.—Section of De Soto-Red River field, Louisiana. Vertical and horizontal scale are the same. Shows curvature of Nacatosh sand from northwest corner of Section 14 to fault in section 23, T. 13 N., R. 11 W. (*Data from Matson and Hopkins.*)

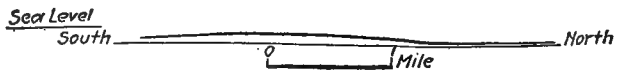


FIG. 72.—Section of Thrall field, Texas. Vertical and horizontal scale are the same. Shows curvature of oil-bearing rock. (*Data from Udden and Bybee.*)

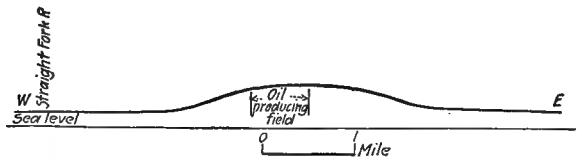


FIG. 73.—Section of Volcano anticline, West Virginia. Shows curvature of Washington coal bed from Straight Fork Creek through town of Volcano to Goose Creek. Vertical and horizontal scales are the same. (*Data from Hennen, West Virginia Geol. Survey.*)

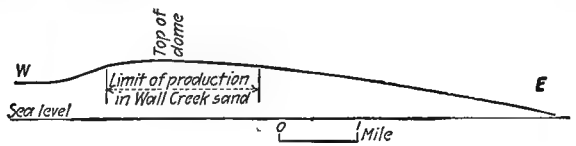


FIG. 74.—Section of Salt Creek dome, Natrona County, Wyoming. Shows curvature of Wall Creek sand from southwest corner of section 27, T. 40 N., R. 79 W. to southwest corner of section 26, T. 40 N., R. 78 W. Vertical and horizontal scale are the same. (*Data from Wegeman, U. S. Geol. Survey.*)

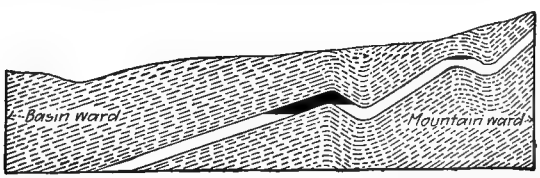


FIG. 75.—Ideal sketch showing oil accumulated principally on the lower anticline or the one on the basinward side of the larger fold; the accumulation is greatest on the basinward limb of the anticline. Black represents oil and gas.

A considerable number of the world's oil and gas fields lie on monoclines that are sealed in various ways. Monoclines may be sealed where impervious rocks meet above the reservoir rock (Fig. 76), at impervious fault planes or where faults throw impervious rocks against the reservoir rocks (Fig. 77), where the



FIG. 76.—Sketch showing reservoir sealed by impervious rocks overlying and underlying the reservoir rock and joining above the reservoir.

sands become impervious by cementation of their interstices or where the interstices were filled with clay particles when the sands were deposited (Fig. 78), or where the oil itself exudes at the surface and on drying hardens to form asphalt (Fig. 79, p. 125). Reservoirs on monoclines may be sealed by fine sand or clay

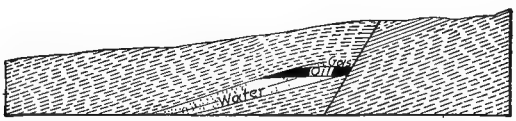


FIG. 77.—Sketch showing reservoir sealed by fault bringing oil sand against impervious rocks.

which gas and oil carry to the roof of the reservoir (Fig. 80). A few oil fields are formed where a tilted eroded petroliferous series is covered unconformably by a later series. If permeable strata such as conglomerates and sandstones are laid down upon the petroliferous strata, the beds of the later series will carry oil.



FIG. 78.—Sketch showing reservoir sealed by tight sand.

If muds or clays cover the petroliferous bed, gas, oil, and water will probably be segregated in the lower or older series. Reservoirs are found at unconformities in many fields.

In the Maikop field, on the north flank of the Caucasus, Russia, oil has accumulated in a sand that was deposited upon an older hilly surface and in turn covered by a impervious bed so that it

is effectively sealed. In the Tampico-Tuxpam field, Vera Cruz, Mexico, petroliferous beds are sealed by igneous intrusives that cut across the beds. It is obvious that monoclines sealed by impervious rocks joining above the reservoir rock and monoclines sealed by local cementation and at unconformities are dis-

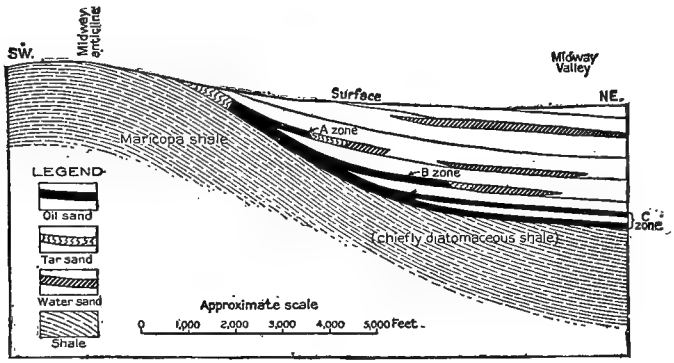


FIG. 79.—Diagram showing relations of productive oil zones in the vicinity of Fellows, Midway-Sunset district, California. (*After Pack.*)

covered with greater difficulty than monoclines sealed by other processes. Oil pools in such positions are discovered, more often than otherwise, by "wildcat" drilling or by wells sunk for water.

Aclines are bodies of rock that lie essentially flat. In such rocks large accumulations of oil are rare. In the Rivadavia

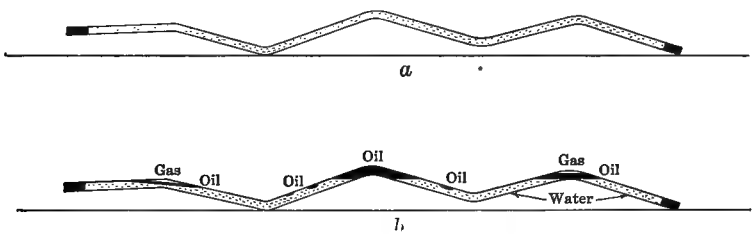


FIG. 80.—Diagrams illustrating accumulation of oil and gas in sand. *a*, Tube filled with sand saturated with oil and acidified sea water; *b*, same tube after dolomite was introduced at both ends. The finer grains of sand were carried to the roof of the reservoir and caused small accumulations of oil to remain low on the central upfold.

field, Argentina, the beds in places are practically flat. At other places they are gently warped.

There is apparently a lower limit of inclination beyond which petroleum will not migrate up the dip. This limit depends on the size of the openings in the rock and the viscosity of the oil.

Where there is a change from a dip up which oil will move to one up which oil will not move an accumulation is likely to take place. If salt water is associated with the oil and the movement is up the dip the accumulation will be near the axis of flexure, where the dip changes, and in general the greatest accumulation will be near the lower edge of the terrace. Such conditions exist in the Peru field, in southern Kansas. On the other hand, if there is no water associated with the oil it tends to move downward, and accumulation may take place on the upper part of the flat limb of the terrace.

Oil is found in synclines in parts of the Appalachian region. In the Catskill strata in Pennsylvania and West Virginia petro-

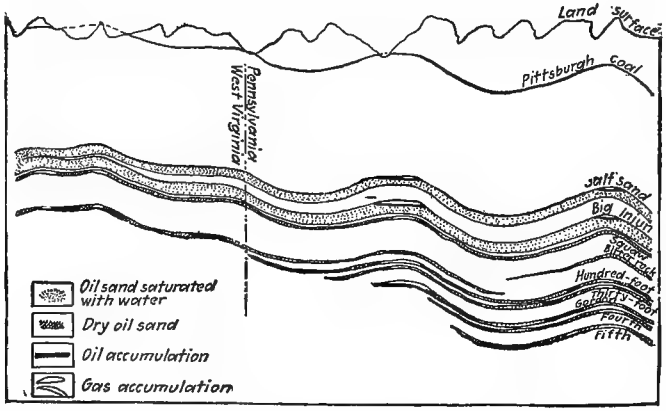


FIG. 81.—Ideal sketch showing accumulation of oil and gas in Appalachian region. The higher sands are saturated, and oil and gas rise to crests of anticlines. The lower sands are not saturated, and the oil and gas are found low on the flanks of the anticlines or in synclines. (*After Griswold and Munn.*)

leum and gas are found in sands between shales. These beds are not saturated with water. The oil occurs in synclines and low on flanks of anticlines. Above these beds the sands are saturated and oil is found near the crests of the folds (Fig. 81).

At Urado, Colorado, in the Uinta Basin, near the Colorado line, oil has been produced from a tunnel driven in a flat-lying sand, the base of which is warped to form gentle sags in which the oil collects. Small amounts of oil have been obtained also near De Beque, in western Colorado, from wells sunk near the axis of a low minor anticline which is developed in a broad syncline. In southeastern Utah a little oil has been found in a syncline in the San Juan field. In the McKittrick district, California, a con-

siderable concentration of oil is found in an overturned syncline. In Galicia also oil is found in synclines in the Boryslaw field.

Practically all consolidated rocks are jointed, or fractured. The earlier investigators of oil reservoirs in the Appalachian region laid much emphasis on fissures as containers of oil and gas. Later, when great fields in unconsolidated rocks were developed in Russia, in California, and elsewhere it appeared less probable that fissures play so important a part, for in soft rocks fissures will close. Dolomitization, has been assumed to form spaces in reservoir rocks. Such openings[1] doubtless add materially to the capacity of reservoirs in certain fields where oil occurs in Paleozoic rocks. In the unconsolidated rocks they are generally less effective.

At Florence, Colorado, the principal reservoirs are fissures in the shale of the Pierre formation. This is a uniform shale, and in the lower part, which carries the petroleum deposits, no sands are present.

In some regions gas is obtained from the shale reservoirs. In Cleveland, Ohio,[2] and in the surrounding country wells have been sunk in the shale for domestic supply. As a rule the pressure is low and the yield small, but the wells have long life.

Orton,[3] describing the differences between shale gas and "reservoir gas," notes that:

Shale-gas wells are generally of small volume, compared to wells deriving their gas from sand reservoirs. Moreover they lack uniformity of rock pressure. Wells drilled in close proximity and to the same depth may have very different pressures. In sand reservoirs pressures are generally greater and more nearly uniform. In the wells yielding shale gas there is no definite horizon from which their gas supply is derived. The stratum that yields it may be several hundred feet thick, and gas is likely to be found at any point in the descent. Shale-gas wells, though in the same field, may be expected to show a considerable range in depth. Some shale-gas wells occur independently of oil production. Gas may be abundant, while petroleum is altogether

[1] LAUER, A. W.: Petrology of Reservoir Rocks and Its Influence on the Accumulation of Petroleum. *Econ. Geol.*, vol. 12, pp. 435–465. 1917.

[2] VAN HORN, F. R.: Reservoir Gas and Oil in the Vicinity of Cleveland, Ohio. Am. Inst. Min. Eng. *Trans.* vol. 54, pp. 831–842, 1916.

[3] ORTON, EDWARD: Geological Survey of the Iola Gas Field. Geol. Soc. America *Bull.*, vol. 10, p. 100, 1899.

wanting. Shale-gas wells are long lived. Weak flows are maintained for long periods. Shale-gas is not dependent on the structural arrangement of the rocks which contain it. If it is not associated with oil or water, it can not be displaced or crowded out by them.

Accumulation in Sands of Irregular Pore Space.—In many oil fields the oil-producing sands are irregular or "spotted." Bor-

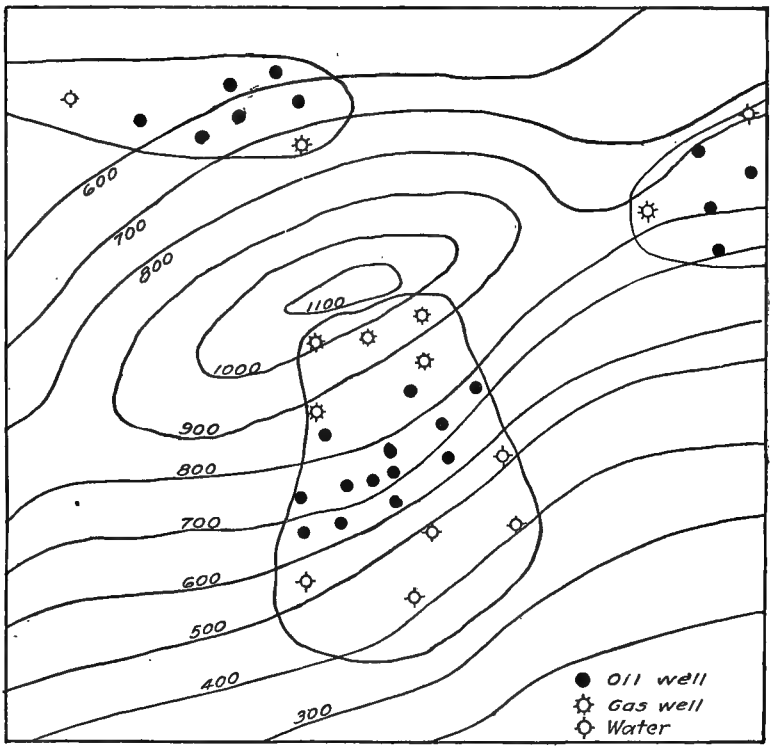


FIG. 82.—Sketch contour map showing accumulations of oil and gas in sands that are only locally pervious.

ings that yield neither oil, gas nor water may be sunk in a sand that contains oil or gas on all sides of it. Examination of fragments of the oil stratum in the boring may discover a tight sand in which the pore space is filled by calcite, pyrite or other secondary minerals, or one that is filled with clay.

On many domes and anticlines, as already noted, a belt that yields oil is found below a disk of gas-filled sand. Some wells,

however, that are sunk in the oil-producing belt may yield gas only. Irregular and fantastic patterns of areas of production are displayed in pools containing "spotted" sands. Nevertheless, in the areas of porous rock that are surrounded by impervious rocks at the same horizon, the oil, gas, and water that are contained in the porous rock are generally segregated in belts, the gas above the oil and the water below it, as is illustrated by Fig. 82. In such a field where pools are not connected by open spaces in the petroliferous stratum the lines of contact between gas and oil and between oil and water may be found at widely different elevations.

Successions of Petroliferous Strata.—In many pools oil is found in more than one stratum. In some it is found in five strata or more. Where the structure is anticlinal and there is an accumulation of petroleum in the upper sand at the crest, it is reasonable to suppose that lower strata, if conformable, lie in anticlines also, and that if they are porous they may contain other reservoirs. In some districts the amplitude of folds increases with depth, and the deeper accumulations, situated on the greater folds, are more productive than the shallow pools. Many fields have been revived again and again by deeper drilling (Fig. 96, p. 153).

Deformation of Petroliferous Strata.—In many districts the petroliferous beds are covered by strata that include considerable thicknesses of unconsolidated clay, marl, or clayey sand. In such districts, even after extensive deformation by folding and faulting, the reservoir rocks may retain large accumulations of oil and gas. In unconsolidated materials openings due to faulting and folding tend to close promptly, so that the oil remains in the reservoir. In such materials there is generally some leakage, however, and oil seeps, asphalt, gas seeps, mud volcanoes, brine springs, and other surface indications of oil or gas are generally found above the reservoirs. Many of the Tertiary oil fields are in highly deformed rocks. These fields in general are marked by prominent surface indications of oil. In consolidated rocks that had undergone so much deformation the gas pressure would have driven the bulk of the available oil from its reservoirs. In consolidated rocks the most productive fields are found in regions that have suffered only gentle deformation. Oil reservoirs in consolidated rocks have doubtless lost their stores by leakage attending thrust faulting and overturned folding. In con-

solidated rocks oil generally is in the simpler structural features only; in unconsolidated rocks it is often found in the most complicated ones, as is shown in many fields in California, Galicia and Rumania. In some of these fields faulting probably took place after accumulation.

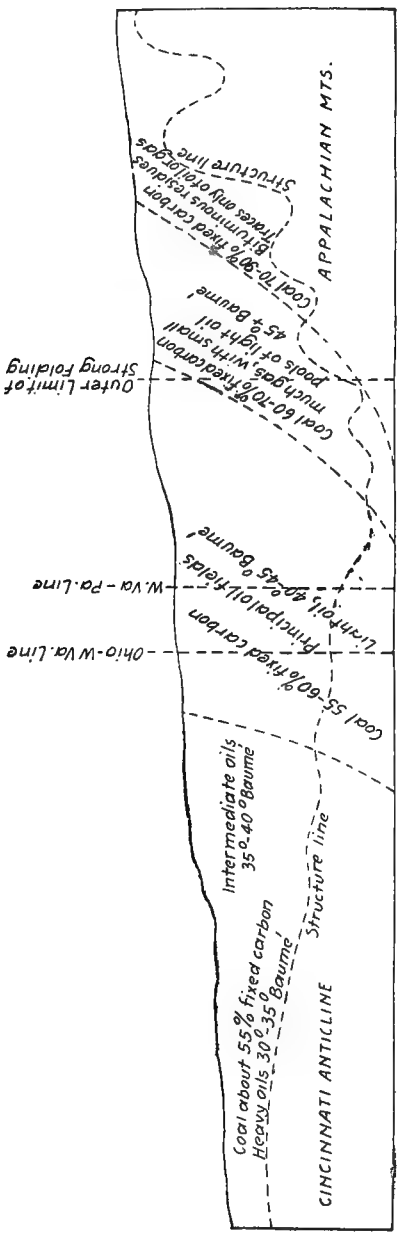


FIG. 83.—Generalized section showing relation of distribution of Appalachian oils of different gravities to the zone of dynamic disturbance and to the fixed-carbon percentages in coals. (*After Fuller.*)

Metamorphism of Petroleum.—Petroleums and the materials of which they are formed are changed by the heat and pressure that attend dynamic metamorphism of strata. In the Appalachian region and in the Mid-Continent field of the United States petroleum and gas are closely associated geographically with beds containing coals, and the degree of metamorphism of the coals affords a kind of index to the intensity of the metamorphic processes. In these regions the coals are altered progressively more toward the areas of intense deformation. The hydrocarbons are driven off and the coal becomes richer in fixed carbon. In the Appalachian region the amount of fixed carbon is greater in the

most highly folded area and decreases toward the west, where the intensity of metamorphism is decreased. Petroleum and gas in reservoirs associated with the coals show differences

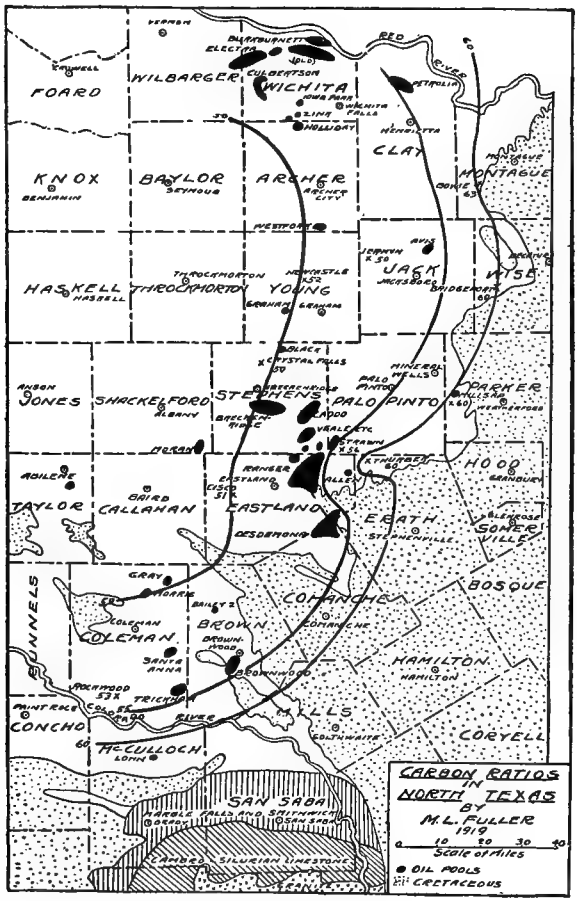


FIG. 84.—Sketch map showing isovols and relation of oil pools to carbon ratios of coals in northern Texas. (*After Fuller.*)

corresponding to the alteration of the coals.[1] This relation between the distribution of oil and the character of coal was

[1] WHITE, DAVID: Some Relations in Origin Between Coal and Petroleum. Washington Acad. Sci. *Jour.*, vol. 5, pp. 189–212, 1915.

discovered by David White[1] and has been treated also by Fuller[2] and by Gardner.[3]

In the Appalachian region, as stated by Fuller, neither oil nor gas, except in a few minor accumulations, has been found east of the west face of the outermost strong fold of the Appalachian Mountains. Between this face and the line of 60 per cent. carbon coals[4] there is much gas in the northern part of the field and some in the southern part, with an oil pool here and there, but the main oil field is west of the 60 per cent. carbon line (see Fig. 83).

In north-central Texas many of the oil pools are associated with strata that contain coals. The coals become richer in fixed carbon toward the east. Nearly all the oil pools lie between the 50 and 55 per cent. isovol[5] (see Fig. 84). In the belt yielding coals that carry between 55 and 60 per cent. of fixed carbon some oil is present, with considerable gas. East of the line showing 60 per cent. fixed carbon no commercial accumulations have been developed.

Gas Pressure.—Whenever petroleum is formed gas is probably generated. Oil absorbs gas, the amount absorbed depending upon the pressure. Whether the oil and gas are formed before or after deformation of the strata, the gas tends to accumulate in the highest parts of a closed fold. If, however, there is enough oil to absorb the gas present at the prevailing pressure, it will

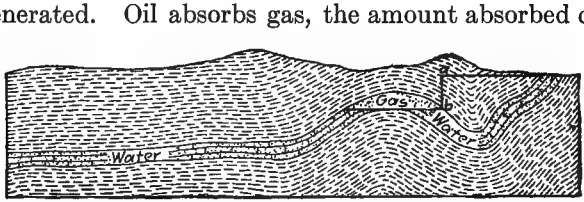


FIG. 85.—Sketch illustrating a gas pool with underlying water body in sand connected freely with surface. Theoretically the pressure should equal the weight of a column of water as high as *ab*.

[1] WHITE, DAVID: Some Relations in Origin Between Coal and Petroleum. Washington Acad. Sci *Jour.*, vol. 5, pp. 189–212, 1915.

[2] FULLER, M. L.: Appalachian Oil Fields. Geol. Soc. American *Bull.*, vol. 28, p. 643, 1917.

[3] GARDNER, J. H.: The Mid-Continent Oil Field. Geol. Soc. America *Bull.*, vol. 28, pp. 685–720, 1917.

[4] A carbon content of 60 per cent. figured ash and moisture free equals a fuel ratio of 1.5 (see page 28).

[5] An isovol is a line connecting points where the coals have equal percentages of fixed carbon (and therefore of volatile matter). See White, David, Washington Acad. Sci. *Jour.*, vol. 5, p. 198, 1915.

be completely absorbed, and oil and gas will issue together from a boring sunk to the top of a high fold.

If the gas accumulates at the top of the fold it exerts a pressure on the oil and tends to drive it to a lower structural position. The oil in turn drives down the water. If the reservoir rock communicates with the surface of the earth at any place and is permeable the water will flow out of the reservoir. Thus the gas pressure will equal the weight of a column of water as high as the difference between the elevation of the gas body and the surface opening where the reservoir rock crops out (see Fig. 85).

In many fields the gas pressure is approximately that of a column of water equal to the depth of the well, but probably in a greater number the gas pressure is much greater or much less than the pressure of such a water column. This shows either that there is no free communication of the reservoir rock with the surface, or that the level of ground water is higher or lower than the top of the well.

Behavior of Certain Wells that Yield Oil and Gas.—Some borings that penetrate reservoirs yield initially large amounts of oil that flows from the well and may be thrown under pressure high above the derrick floor. Such wells are termed "gushers." They are characteristic of fields that have reservoirs containing gas under high pressure. Production may increase for a few days while draining lines are being established in the reservoir, but almost invariably the initial production declines rapidly after a short period. The gas, under pressure, forces out the oil into the boring and causes it to rise vertically. Sand and gravel frequently rise with the oil and gas. A well that penetrates only the top of a sand reservoir may "drill itself in," or sink to the bottom of the reservoir while sand is being expelled with the oil.

As gas is the agent that forces oil out of the rocks into the wells, its pressure is of great economic interest. In porous rocks the decline of gas pressure over a field is approximately uniform. Every thousand feet of gas that is lost in general tends to lower the pressure.

Some wells that at first yield gas subsequently yield oil. Indeed, it is a common, though wasteful practice to allow gas to escape from a well in the hope that ultimately the well will produce oil. Not only is the gas wasted, but oil also is likely to be wasted, because the gas is the means by which the oil is expelled from the rocks. If a small pocket of gas has accumu-

lated at some high point in the roof of a reservoir and is punctured by a drill gas will rise first and later oil, which is under pressure. This is illustrated in well 1, Fig. 86. If a gas well is on the flank of a fold near the contact of gas and oil, it is obvious that release of the gas pressure which holds the oil down will permit the oil to rise higher in the reservoir, or to be pushed up by water pressure. Thus in well 2, Fig. 86, gas would issue first and oil later. Some wells yield petroleum first and salt water later. Well 3, Fig. 86, would start as a petroleum well, and as the pressure declined and petroleum was removed from the reservoir, salt water would rise to take its place. Many petroleum wells become salt-water wells.

Many oil wells flow by heads, or spout periodically like geysers. The bore is gradually filled with oil and gas, accumulated below, until the pressure is sufficient to cause the oil to overflow. As the

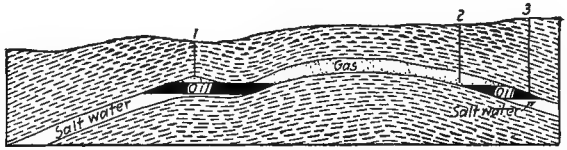


FIG. 86.—Sketch showing gas wells (1 and 2) that would become oil wells if, because of decrease of pressure of gas, the plane of contact of oil and gas were to rise. If the plane of contact between oil and water were elevated because of removal of gas or oil, well 3 would cease to flow oil and would flow water.

oil flows out the casing head, pressure is relieved and that allows the gas to expand suddenly and to raise the column of oil with force.

Some flowing wells, after being capped and reopened will cease to flow. In some cases the gas pressure has been reduced by other wells tapping the reservoir between the time of closing and reopening the well.

Paraffin wax is dissolved in oil. Cooling follows relief of pressure and causes precipitation. In some wells the wax is deposited in quantities so great as to retard production.

The life of most wells is comparatively short. Some start flowing at high rates, many spouting 5,000 or 10,000 barrels a day or more. As a rule they decline rapidly and steadily after they have reached their maximum, which is generally during the first few days. The first year's flow is usually much greater than the yield of any other year.

In estimating the future production of a field, two methods are employed. In one curves are prepared to show the rate of decline.[1] In the other the volume, porosity, and saturation of the sands and the amount of oil which may eventually be recovered are estimated from the data available. Each method exhibits certain advantages under certain sets of conditions.

It is noteworthy that not only does the yield of individual wells diminish rapidly, but the initial yields and total production of wells generally diminish steadily as more wells are put down in the field.

Probably half the oil in some reservoirs remains in the rocks after the fields have ceased to yield. It adheres to sand grains, and in the absence of gas under pressure it can not be moved (Fig. 87). By proper management and conservation of gas pressure, the maximum yields may be obtained. If the gas is tapped above the oil and the gas pressure is wasted without allowing the gas to do its work, it may be impossible to obtain the principal part of the oil stored in the rocks. It is common practice to increase the flow by pumping the sands to a vacuum. Another method consists in driving water into the sands and floating the oil to points of issue. Thus water that is allowed to enter the sands in one well will make its way down the dip to another well, pushing the oil ahead of it. A third method consists in pumping compressed air into the sands. Natural gas is used in some fields instead of air and has the advantage that it absorbs the gasoline, which may be recovered by condensing the gas after it has issued from the wells. These methods[2] prolong the life and increase the

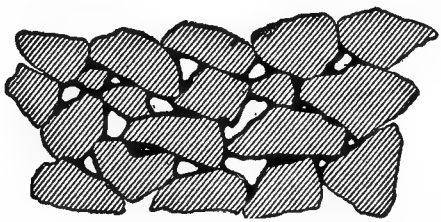


FIG. 87.—Sketch illustrating a pile of sand grains, showing how oil is retained by adhesion. (*After Lewis.*)

[1] BEAL, C. H.: The Decline and Ultimate Production of Oil Wells, with Notes on the Valuation of Oil Properties. U. S. Bureau of Mines *Bull.* 177, pp. 1–215, 1919.

[2] LEWIS, J. O.: Methods for Increasing the Recovery from Oil Sands. U. S. Bureau of Mines *Bull.* 148, pp. 1–128, 1917.

production of a field, but they are generally not employed until the field is near exhaustion.

Petroliferous Provinces.—The term "petroliferous province," first used by Woodruff,[1] suggests a region containing accumulations of petroleum that are nearly related genetically and that have closely similar geologic surroundings.

Schuchert[2] classifies areas as regards petroliferous possibilities as follows:

1. The impossible areas for petroliferous rocks.
   (*a*) The more extensive areas of igneous rocks and especially those of the ancient shields; exception, the smaller dikes.
   (*b*) All pre-Cambrian strata.
   (*c*) All decidedly folded mountainous tracts older than the Cretaceous; exceptions, domed and block-faulted mountains.
   (*d*) All regionally metamorphosed strata.
   (*e*) Practically all continental or fresh-water deposits; relic seas, so long as they are partly salty, and saline lakes are excluded here.
   (*f*) Practically all marine formations that are thick and uniform in rock character and that are devoid of interbedded dark shales, thin-bedded dark impure limestones, dark marls, or thin-bedded limy and fossiliferous sandstones.
   (*g*) Practically all oceanic abyssal deposits; these, however, are but rarely present on the continents.
2. Possible petroliferous areas.
   (*a*) Highly folded marine and brackish water strata younger than the Jurassic, but more especially those of Cenozoic time.
   (*b*) Cambrian and Ordovician gently folded strata.
   (*c*) Lake deposits formed under arid climates that cause the waters to become saline; it appears that only in salty waters (not over 4 per cent.?) are the bituminous materials made and preserved in the form of kerogen,

[1] Woodruff, E. G.: Petroliferous Provinces. Am. Inst. Min. Eng. *Bull.* 150, pp. 907–912, 1919.

[2] Schuchert, Charles: Petroliferous Provinces; Discussion of Paper of E. G. Woodruff. Am. Inst. Min. Eng. *Bull.* 155, p. 3059–3060, 1919.

the source of petroleum; some of the Green River (Eocene) continental deposits (the oil shales of Utah and Colorado) may be of saline lakes.

3. Petroliferous areas.
   (*a*) All marine and brackish water strata younger than the Ordovician and but slightly warped, faulted, or folded; here are included also the marine and brackish deposits of relic seas like the Caspian, formed during the later Cenozoic. The more certain oil-bearing strata are the porous thin-bedded sandstones, limestones, and dolomites that are interbedded with black, brown, blue, or green shales. Coal-bearing strata of fresh-water origin are excluded. Series of strata with disconformities may also be petroliferous, because beneath former erosional surfaces the top strata have induced porosity and therefore are possible reservoir rocks.
   (*b*) All marine strata that are, roughly, within 100 miles of former lands; here are more apt to occur the alternating series of thin and thick-bedded sandstones limestones and interbedded shale zones.

CHAPTER V

OIL FIELDS, OIL SHALES AND ASPHALTS

UNITED STATES

Appalachian Oil Field.—The Appalachian oil field lies northwest of the Appalachian Mountains, mainly in New York, Pennsylvania and West Virginia, extending into eastern Ohio, Kentucky, and Tennessee. It was the first great oil field to be developed and still yields about 25,000,000 barrels annually.

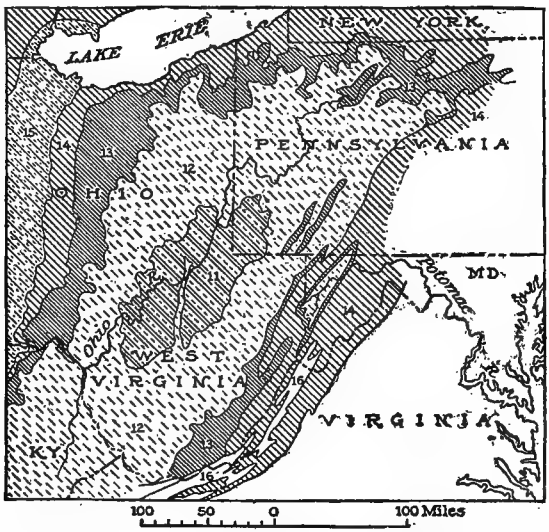


FIG. 88.—Sketch showing the areal geology of part of the Appalachian geosyncline. 11, Permian; 12, Pennsylvanian; 13, Mississippian; 14, Devonian; 15, Silurian; 16, Ordovician. (*After Willis.*)

Surface indications of oil include several oil and gas springs in New York, Pennsylvania, and West Virginia and the great grahamite dike in West Virginia.

The field is a great geosyncline (Fig. 88) that extends from northern Alabama to New York. On this are developed many minor folds (Figs. 89, 90). These strike northeast, parallel to the axis of the syncline, except the Volcano anticline, which strikes north.

PRELIMINARY SUMMARY OF PETROLEUM PRODUCED IN THE UNITED STATES IN 1919, BY FIELDS

Field	Quantity (barrels)	Value	Field	Quantity (barrels)	Value
Appalachian	29,232,000	$110,000,000	Rocky Mountain	13,584,000	$21,000,000
Lima-Indiana	3,444,000	8,000,000	California	101,564,000	135,000,000
Illinois	12,436,000	31,000,000			
Mid-Continent	196,891,000	447,000,000		377,719,000	775,000,000
Gulf	20,568,000	23,000,000			

The rocks are of Paleozoic age and range from Cambrian to Permian. Oil is found in considerable amounts in Devonian,

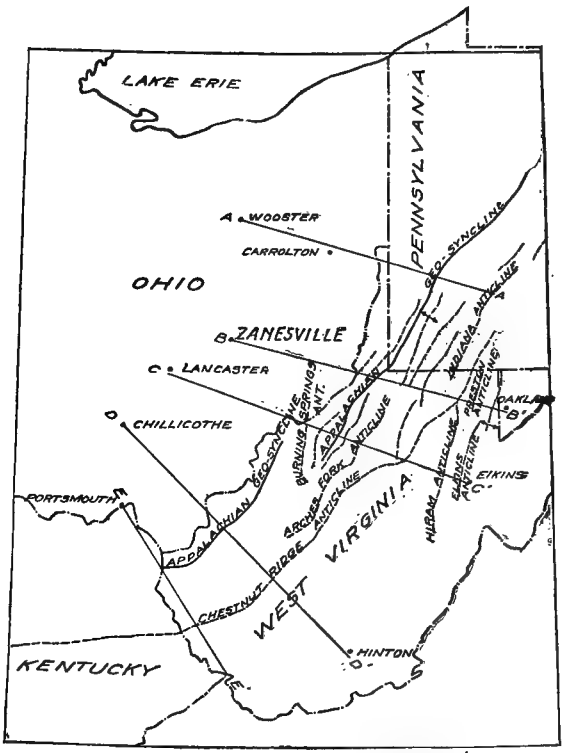


FIG. 89.—Map showing axes of folds in part of Appalachian geosyncline. For sections along lines *A-A'*, etc., see Fig. 90. (*Based on Map by Reger.*)

Mississippian, and Pennsylvanian rocks. Gas is found in these rocks and also in the lower Paleozoic sediments including the Cambrian. The oil is of high grade, has a paraffin base, and is easily refined. There are scores of pools in this region. Among

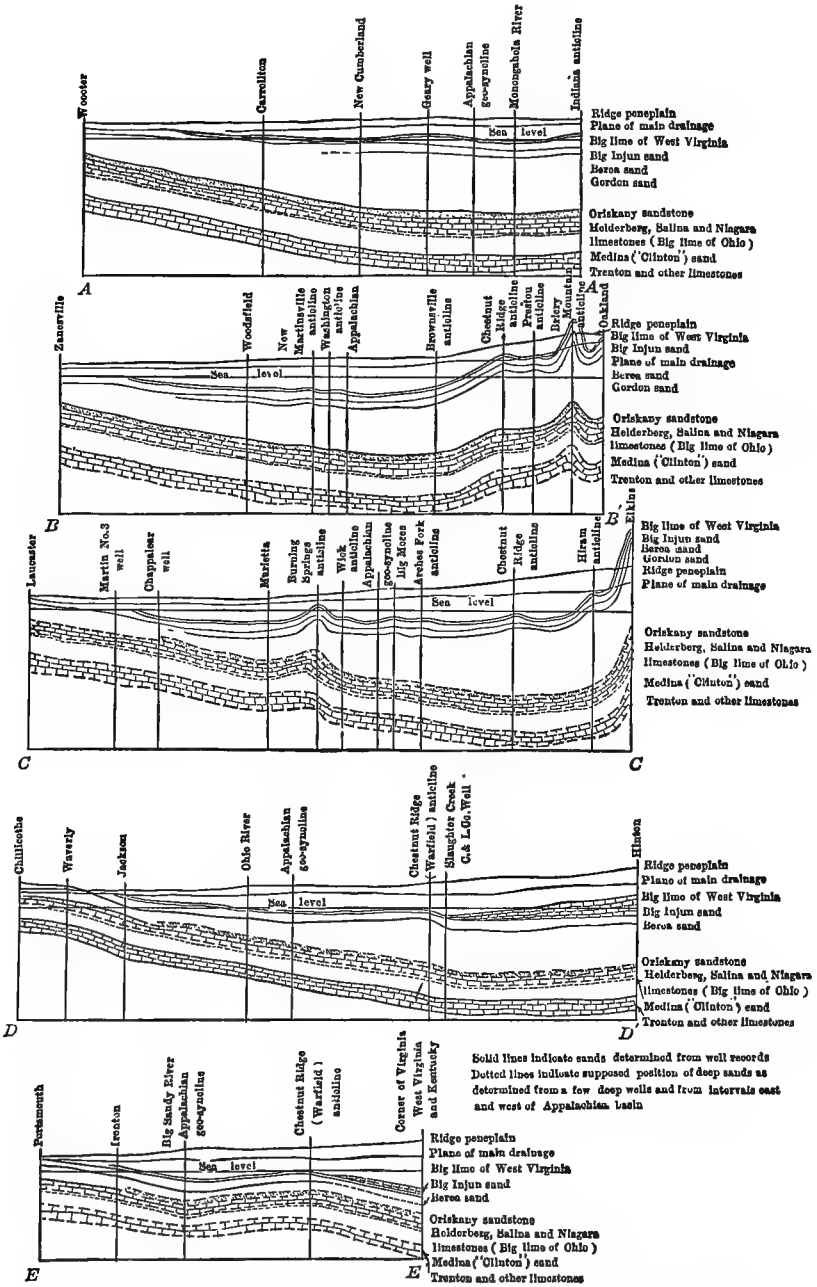


FIG. 90.—Cross-sections showing positions of folds in part of the Appalachian geosyncline. For lines of section, see Fig. 89. (*After Reger.*)

the larger ones are the Bradford pool, in New York and Pennsylvania, in which the oil is found in the Devonian; the Venango sand pools in Pennsylvania, in which the Devonian and Mississippian are productive; and the Volcano field, in West Virginia, and nearby pools, in which oil is derived from Mississippian and Pennsylvanian rocks. Nearly all the oil is found in sandstones, which are covered with shales. Some of the sands are saturated with salt water and gas, and in these the oil is found above the water, near the crests of folds. Other petroliferous strata are not saturated, however, and in these the oil is found well down on the folds, and where the folds are dry the oil may extend to the synclinal trough. In general the contacts between oil and gas and between oil and water follow the structural contours.

Much of the oil-bearing region also contains coal. Toward the southeast the percentage of fixed carbon increases in the coal. As shown by White (p. 130) there is little or no oil southeast of the line where coals carry as much as 65 per cent. of fixed carbon.

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Oil and gas are found also in Kentucky and Tennessee and East Ohio. In Kentucky[1] and Tennessee oil is found at scores

[1] JILLSON, W. R.: The Oil and Gas Resources of Kentucky. Kentucky Dept. Geology and Forestry, ser. 5, vol. 1, pp. 1–630, 1919.

of places, although few of the fields are highly productive. The Irvine field[1] yields from Devonian limestone; other fields yield from Silurian, Ordovician, and Carboniferous sandstones or limestones.

The Clinton gas field, in eastern Ohio, is one of the most productive gas fields in the world. The gas comes from the "Clinton" (Medina) sand and is accumulated on a monocline (Fig. 91) which is sealed above, where the Clinton pinches out between the impervious rocks. A little oil also is found here and there in the Clinton. In Eastern Ohio oil and gas are found also in Paleozoic beds above the Clinton.

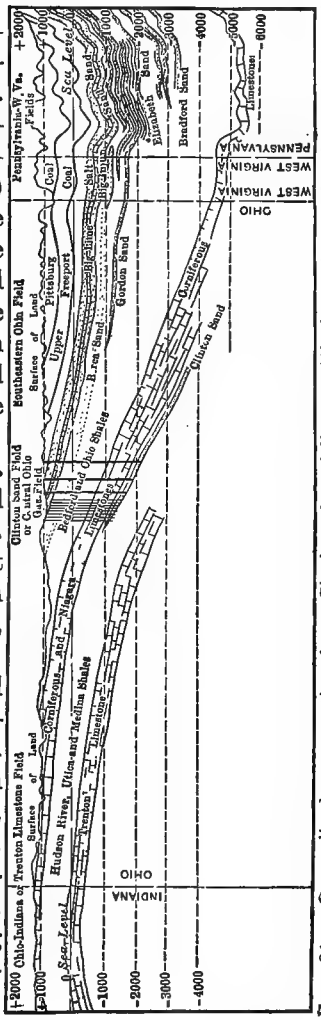


FIG. 91.— Generalized cross-section from Cincinnati anticline to Allegheny front, showing position of wells in "Clinton" field of central Ohio. (*After Clapp.*)

Lima-Indiana or Trenton Field. The Trenton limestone oil and gas field of Ohio and Indiana (Fig. 92) occupies a large area that extends with interruptions from Lake Erie to a point near Marion, Indiana.[2]

Surface indications of oil and gas are rare in this field. Nevertheless they led to its development. Prospecting was first carried on in the vicinity of Findlay, Ohio, where gas seeps were common. These seeps led to the development of the Findlay pool in 1865. This pool was shown by drilling to be on a structural dome having about 200 feet of closure.

[1] SHAW, E. W.: The Irvine Oil Field, Estill County, Kentucky. U. S. Geol. Survey *Bull.* 661, pp. 141–192, 1918.

[2] BOWNOCKER, J. A.: Petroleum in Ohio and Indiana. Geol. Soc. America *Bull.*, vol. 28, p. 670, 1917.

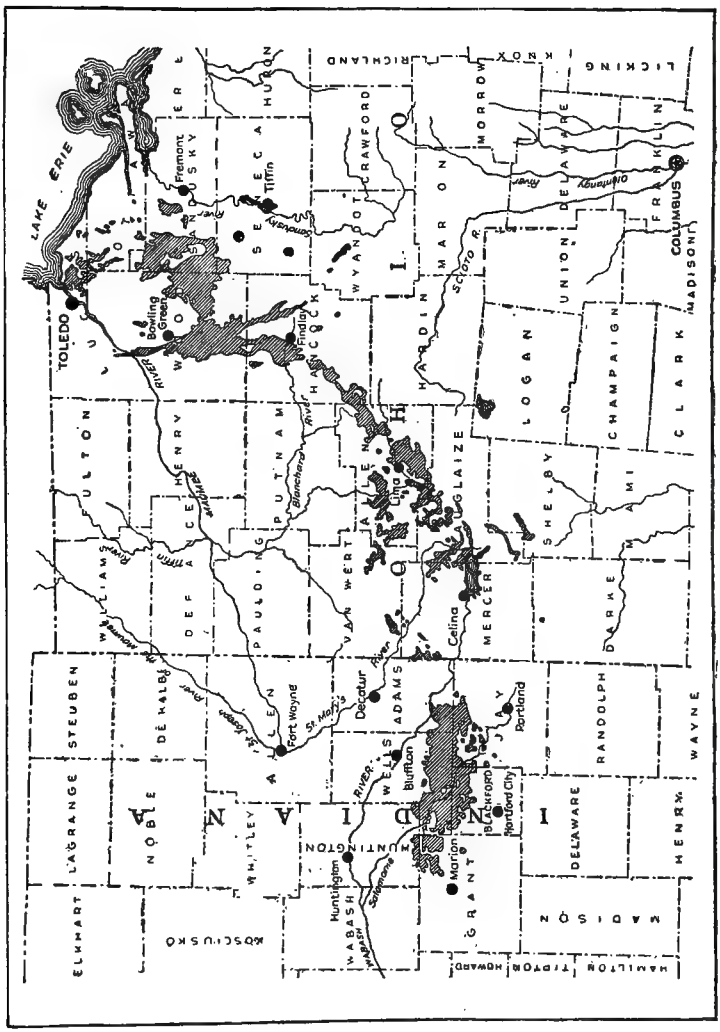


FIG. 92.—Map showing the Trenton (Lima-Indiana) oil and gas field in Ohio and Indiana. (*After Bownocker.*)

The rock succession is shown by the following well records.[1]

OHIO

	Thickness (feet)
Niagara limestone	167
Niagara shale and Clinton limestone	108
Medina shale	47
Hudson River shale and limestone	462
Utica shale	300
Trenton limestone at	1,092

INDIANA

	Thickness (feet)
Niagara limestone	153
Hudson River limestone	451
Utica shale	300
Trenton limestone at	954

The region is a broad, flat-topped arch that has formed as a warping on the Cincinnati, anticline. In Ohio part of the richest territory has been found on this arch, but in Indiana it does not appear on the summit of the arch, but on the north side, where the rock dips to the northeast. The Trenton limestone nearly everywhere in these two States contains brine below the oil.[2]

The Trenton in the producing region has a high porosity, which, according to Orton, has been developed by dolomitization of limestone. He cites many analyses to show that the Trenton where oil-bearing is much richer in magnesium than where it is barren of oil.

Around the gas field salt water rises to nearly equal altitudes on all sides. Although the Trenton is porous on both sides of the arch over northern and central Indiana, in the southeastern part of the State it is more compact. The main body of the arch may be regarded, then, as a long inverted trough or flat tube having its south end closed and its north end immersed in the salt water, which is forced up into and around it by the hydrostatic pressure of the water. The pressure is due to the pressure of the water around the sides of the arch. The Cincinnati arch is a dome surrounded by a larger basin. The water descends down the

[1] Orton, Edward: Ohio Geol. Survey, vol. 6, p. 112, 1888.

Blatchley, W. S.: Indiana Dept. Geology and Nat. Res., *Twenty-first Ann. Rept.*, p. 68, 1897.

[2] Orton, Edward: Ohio Geol. Survey, vol. 6, p. 46, 1888.

Orton, Edward: The Trenton Limestone as a Source of Petroleum and Inflammable Gas in Ohio and Indiana. U. S. Geol. Survey *Eighth Ann. Rept.*, part 2, pp. 475–662, 1889.

slopes of the basin and rises in the arch, pushing oil and gas ahead of it, and equilibrium is established by the back pressure of gas when it equals the water pressure.

Michigan Field.—The southern peninsula of Michigan is structurally a great basin whose long axis trends north.[1] Strata from the Ordovician to Pennsylvanian crop out or are discovered in drill holes. In the eastern part of the peninsula small folds are probably developed on the westward-dipping beds (Fig. 93). At Port Huron oil is obtained from the Dundee formation (Onondaga or "Corniferous"), which is chiefly limestone. This formation is also the source of oil in Lambton County, Ontario, east of Port Huron. (See p. 183.) The Port Huron wells have produced oil since 1900, but the yield has never been large.

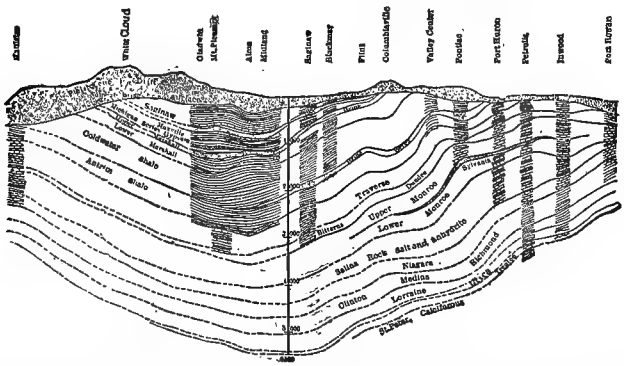


FIG. 93.—Diagrammatic cross-section of the Michigan basin from Port Rowan, Ontario, to Manistee, Mich. (*After Smith.*)

The oil of Michigan is of good grade and rich in the lighter spirits. Gas and salt water are associated with it.

Illinois Fields.—Petroleum is found at a number of places in Illinois, but none of the fields have been highly productive except the one in southeastern Illinois, in Crawford and adjoining counties. This field was discovered in 1905 and was rapidly developed. There are no oil springs in this field, although oil seeped into a mine through a drill hole sunk while prospecting a neighboring field for coal. The oil field is on and near the crest of the La Salle anticline, and the oil generally is floated on salt water, rising to the higher parts of the folds (Fig. 94). The

[1] SMITH, R. A.: The Occurrence of Oil and Gas in Michigan. Michigan Geol. and Biol. Survey *Pub.* 14, *Geol. ser.* 11, pp. 1–281, 1914.

oil is found in rocks of Mississippian and Pennsylvanian age. These are porous sands, except the McClosky "sand," near the bottom of the series, which is a porous oolitic dolomite. The covering strata are shales. In parts of this field oil has been found also in the Trenton limestone.

In the west-central part of Illinois oil or gas or both have been discovered on several domes outlined by the Illinois State Geological Survey, by running accurate levels on coal beds that lie above the oil-bearing strata.

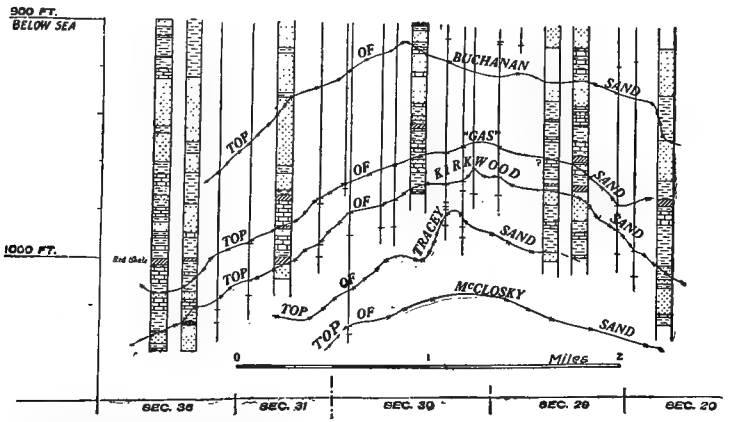


FIG. 94.—Section across dome in oil field in Petty Township, Lawrence County, Illinois. The surface of the ground is about 1,000 feet above the top of the section. (*After Blatchley.*)

Among these smaller fields are the Staunton, Carlinville, Litchfield, Carlyle, and Greenville fields, in all of which the oil or gas is found in Pennsylvanian and Mississippian sands. In the Colmar field, in western Illinois, oil is found in sandstone lenses (Hoing sand) at the base of the Niagara limestone. In Pike County gas occurs in a porous limestone that probably belongs to the Niagara.

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Mid-Continent Fields.—The Mid-Continent oil fields include the oil-producing areas of Oklahoma, Kansas, and Missouri, the producing region of Arkansas, and the fields of northern and central Texas and northern Louisiana. The principal producing areas are in Kansas, Oklahoma, and northern Texas and Louisiana. In these fields oil is obtained from Carboniferous and Cretaceous strata. In the principal fields of Kansas and northern Oklahoma the sand members associated with Cherokee shales produce nearly all the oil. In southern Oklahoma and northern Texas near Red River oil is obtained from sandstones of the Pennsylvanian and from sandstones that are correlated with the Permian (Red Beds) by some investigators and with the upper Pennsylvanian by others. These beds produce gas and oil in the Healdton and neighboring districts. In the Ranger region, northern Texas, oil is found in the Bend series (Mississippian). In central Texas and northern Louisiana oil is found in Cretaceous sandstones and chalks.

In the Mid-Continent fields oil and gas occur on domes, anticlines, structural noses, structural terraces, and fluted monoclines. On the whole the structural features are somewhat less accentuated than those in the Appalachian oil fields, and the porous rocks are more generally filled with salt water. The oil saturation is greater than in most other fields, and structural elevations with less than 20 feet of closure are searched for diligently and explored.

The major uplifts in this region are the Ozark dome, the Ouachita "orographic element," including the Ouachita, Arbuckle, and Wichita mountains, the Llano-Burnet uplift of Texas,

and the Sabine uplift. Although the Ouachita element is more highly deformed than the Ozark dome, the structure of the Ozark is more far-reaching, for the beds dip westward far away from the Ozark center, and southwestward within a comparatively short distance of the Ouachita element.

Oklahoma.—The northeastern Oklahoma and southeastern Kansas fields are treated as a structural and stratigraphic unit. East of the area which includes them, extending from northern Missouri almost to Muskogee, Oklahoma, are found Mississippian and older rocks. From Muskogee County, east and southwest to the Arbuckle Mountains is an area containing many gas fields, of which it is said that any oil present may have been vaporized or scattered by metamorphism attending the faulting of the Ouachita element. West of this area in Oklahoma and Kansas the petroliferous rocks are covered by Permian beds, and in that direction limits to the oil fields can not be set. In northeastern Kansas Pennsylvanian rocks are found, but the territory is not known to be petroliferous.

The rocks that crop out in the area are Pennsylvanian and lower Permian. The beds strike about N10°–20° E. and dip west about 30 feet to the mile. Locally the dip increases, and on folds it becomes 100 feet to the mile or more. Reverse dips are rarely more than 1°.

The oil and gas are found in sands and very subordinately in thin-bedded porous limestones. Most of the productive sands are in the Cherokee shale series, above the Mississippian. Recently some oil has been found in the Mississippian limestone. The shales of the Cherokee are generally dark colored or black and carry bands of highly bituminous material.

The Bartlesville sand is by far the most productive, having supplied 90 per cent. or more[1] of the oil produced in Oklahoma and Kansas up to 1919.

In the Bartlesville region it is from 30 to 60 feet thick. It has an average porosity of 20 per cent. McCoy[2] states that the pay sands where thickest show many partings of black shale. Oil and gas seeps are very rare in this area, and at most pools they are lacking.

[1] Gardner, J. H.: Mid-Continent Geology. *Oil and Gas Journal Suppl.*, May 30, 1919.

[2] McCoy, A. W.: Notes on Principles of Oil Accumulation. *Jour. Geol.* vol. 27, p. 252, 1919.

The Permian beds contain gas on the Blackwell anticline, on the Garber dome, and on the Billings anticline.

The location of the fields in Oklahoma is shown by Fig. 95. In the northeastern Oklahoma and southeastern Kansas field the larger number of oil and gas bearing districts are on low domes or low anticlines, although a considerable number are on terraces. Some of the productive folds are isolated structural features with clearly defined boundaries, like the domes of the Cushing field, Garber, and many others. Other fields are located on zones of gentle crumpling, like the Bartlesville area in Osage County and the areas in Washington County, to the east of it. Although these folds are gentle, many of them are easily recognized on account of numerous exposures. In many of the districts there is an abundance of salt water under strong pressure. In such districts the oil and gas lie above the water. Where the sands lie deep, segregation is more pronounced.

Production in Oklahoma (Fig. 95) has come mainly from Nowata, Washington, Osage, Kay, Rogers, Tulsa, Pawnee, Garfield, Wagoner, Creek, Muskogee, and Okmulgee counties. In the eastern part of the field the oil is obtained from shallower wells than in the western part, where the Cherokee series lies below a great thickness of strata. In the eastern part of the field the pools are not all related to clearly defined folds, although production is generally controlled by slight crumples of the strata. In Kay, Garfield, Noble, Creek, and Pawnee counties, the greater concentrations are in clean-cut anticlines or on definitely closed folds. Noteworthy among these features are the Cushing, Garber, and Ponca City folds.

The Cherokee formation, the principal oil and gas producing member of the Pennsylvanian series in Kansas and northeastern Oklahoma, contains the Squirrel, Skinner, Red Fork, Nemire, Bartlesville, Tucker, Dutcher, and other sands. In some districts five or six sands are productive.

The Cushing[1] oil pool is mainly in western Creek County but extends westward into Payne County. The Pennsylvanian rocks exposed at the surface lie near the top of that series. Between

[1] Buttram, Frank: The **Cushing Oil and Gas Field, Oklahoma.** Oklahoma Geol. Survey *Bull.* 18, pp.1–60, 1914.

Beal, C. H.: Geologic Structure in the Cushing Oil and Gas Field, Oklahoma, and Its Relation to the Oil, Gas, and Water. U. S. Geol. Survey *Bull.* 658, pp. 1–64, 1917.

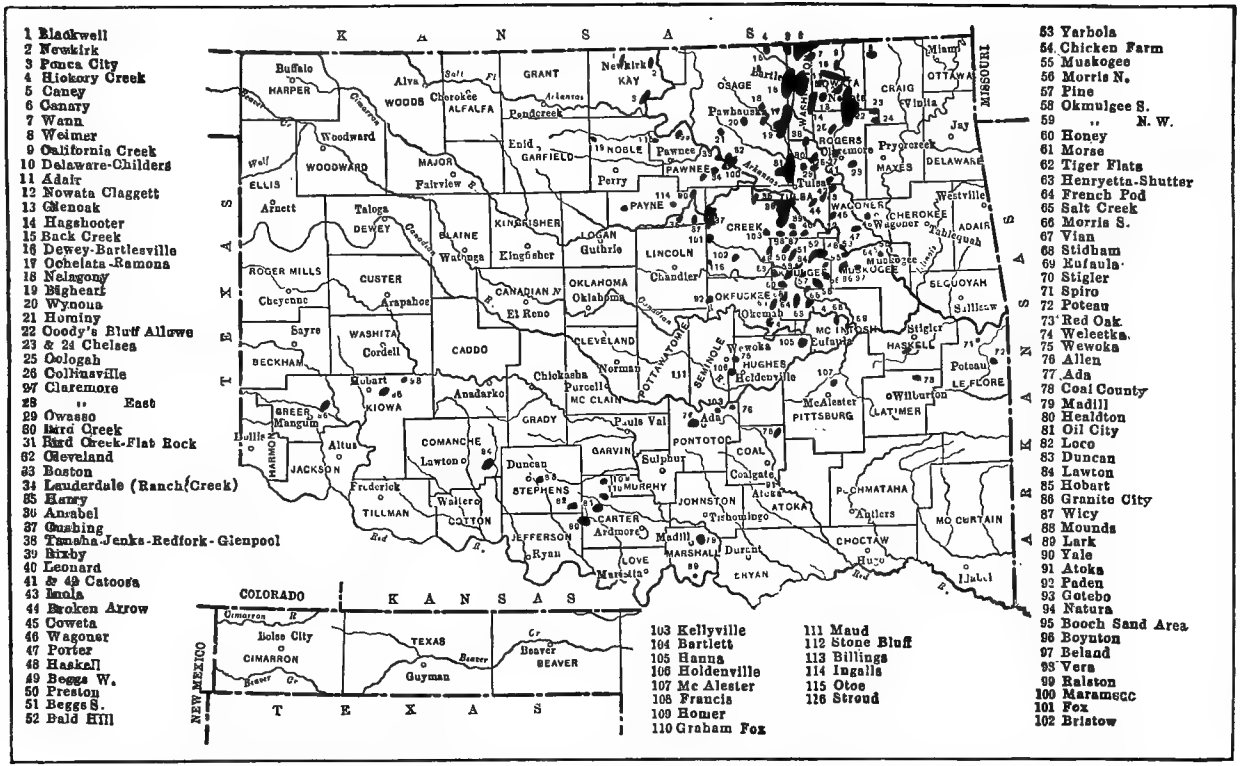


FIG. 95.—Map of Oklahoma showing areas of oil and gas development. (*After Shannon and others.*)

the western limit of the field and the upper or western limit of the Pennsylvanian series about 400 feet of strata crop out, including the Neva limestone and representatives of the Elmdale and underlying formations. The line between the Pennsylvanian and Permian is drawn by Beal at the base of the Cottonwood limestone, which is about 50 feet above the Neva limestone. The following are the Pennsylvanian strata, the youngest at the top.

Neva limestone.
Sandstones and shales and thin limestones (556. 5 feet).
Pawhuska limestone. Is 2,340 feet above Fort Scott limestone and 1,243 to 1,262 feet above Lost City limestone.
Shale and sandstones (134 feet).
Elgin sandstone.
Interval.
Lost City limestone.
Interval (1,078 to 1,097 feet). Includes Layton sand at 700 to 810 feet above Wheeler sand.
Fort Scott or Oswego limestone (75 feet) (= Wheeler sand).
Interval.
Bartlesville sand (in Cherokee shale).

The most prominent outcropping stratum is the Pawhuska limestone. Oil is produced from six sands, the Layton, Jones, Wheeler, Skinner, Bartlesville, and Tucker.

The dominant structural feature in the Cushing field is a broad anticlinal fold (Fig. 96) with domes along its axis and many subsidiary folds and irregularities along its sides. This great fold is one of the largest structural features in northern Oklahoma. The oil and gas are found at the top of the anticline. Below the oil is salt water.

The Glenn pool, which is southwest of Tulsa and about 30 miles east of the Cushing pool, is one of the most productive of the Mid-Continent field.[1]

The strata dip slightly north of west about 50 feet to the mile, and the structure is complicated by a system of folds whose axes roughly parallel the direction of general dip. The oil and gas occur in several sands, the field extending westward down the monoclinal dip. Both upward and downward flutings carry oil. The monocline is believed to be sealed by tighter sands above the productive portion of the field.

[1] Smith, C. D.: The Glenn Oil and Gas Pool and Vicinity, Oklahoma. U. S. Geol. Survey *Bull.* 541, pp. 34–48, 1914.

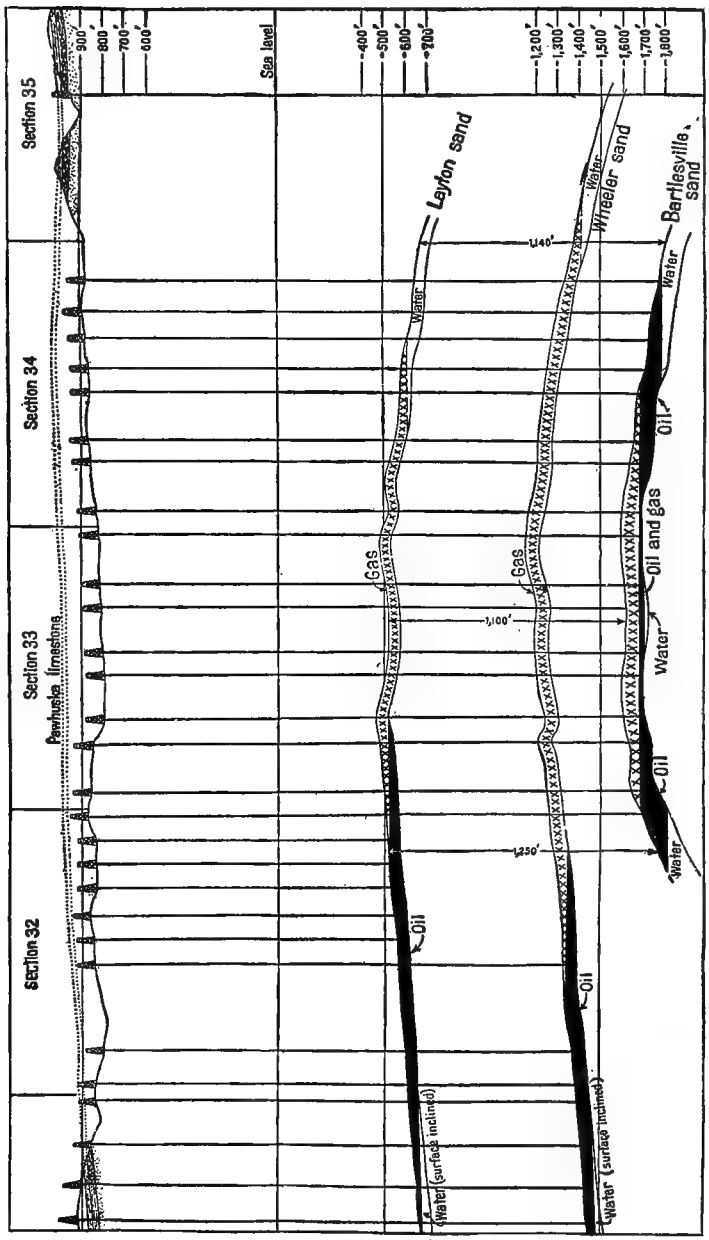


FIG. 96.—Sketch section along south line of T. 18 N., R. 7 E., through the Drumright dome, Cushing field, Oklahoma, showing the stratigraphic relations of the Pawhuska limestone and the Layton, Wheeler and Bartlesville sands, the increase in the Layton-Bartlesville interval, and the inclination of the water surfaces. (*After Beal.*)

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Arkansas.—The Fort Smith-Poteau gas field[1] is south of Fort Smith, in Arkansas and Oklahoma. Natural gas was discovered some years ago in Massard Prairie, 5 miles southeast of Fort Smith, and also about 2 miles southeast of Mansfield, Arkansas, and more recently it has been found 3 miles east of Poteau, Oklahoma.

The rocks are Pennsylvanian. The reservoirs are sandstones which are thrown into folds. The gas is found in anticlines.

Kansas.—In Kansas, which contains the northern part of the Mid-Continent field, the geologic conditions are essentially similar to those in Oklahoma, already described. The rocks that crop out in Kansas[2] are all sedimentary beds. The oldest rocks are Mississippian strata, which are exposed only in the southeast corner of the State. To the west and north is a broad area of Pennsylvanian strata that extends to the north boundary. West of that is a belt of Permian beds, narrow at the Nebraska line and very broad at the Oklahoma line. West of the Permian belt is a broad area of Mesozoic and Cenozoic beds that extends to the west border of the State.

The oil and gas are found mainly in the Cherokee formation, which is the principal producing formation in northern Oklahoma, Some oil has been found in the Mississippian

The strata of Kansas dip northwest, away from the Ozark uplift, in general at the rate of 30 feet to the mile or less. The deposits are on the great westward-dipping monocline, and the minor structural features that localize the accumulations are mainly anticlines, domes, flutings on monoclines, or structural terraces.

In Kansas granite occurs at relatively shallow depths on some of the domes. At Elmdale, Onaga, Wabaunsee, and Zeandale

[1] SMITH, C. D.: Structure of the Fort Smith-Poteau Gas Field, Arkansas and Oklahoma. U. S. Geol. Survey *Bull.* 541, p. 23, 1914.

[2] HAWORTH, ERASMUS, and others: Special Report on Oil and Gas. Kan. Geol. Survey, vol. 9, pp. 1–586, 1908.

SCHRADER, F. C., and HAWORTH, ERASMUS: Economic Geology of the Independence Quadrangle, Kansas. U. S. Geol. Survey *Bull.* 296, pp. 1–74, 1906.

ADAMS, G. I., HAWORTH, ERASMUS, and CRANE, W. R.: Economic Geology of the Iola quadrangle, Kansas. U. S. Geol. Survey *Bull.* 238, pp. 1–83, 1904.

ADAMS, G. I.: Oil and Gas Fields of the Western Interior and Northern Texas Coal Measures and of the Upper Cretaceous and Tertiary of the Western Gulf Coast. U. S. Geol. Survey *Bull.* 184, pp. 1–64, 1901.

granite is encountered at stratigraphic horizons as high as 1,000 feet above the base of the Pennsylvanian series.

The buried granite ridge is shown by Moore[1] to extend from Kay County, Oklahoma, across Kansas into Nebraska. Wells penetrating granite are numbered on Fig. 97*A*. As shown by Fig. 97*B*, the buried granite ridge is nearly straight and its greatest relief is over 3,000 feet. It is lower in the southern part of the State, where in Butler County the great Eldorado and Augusta fields are in domes on top of the granite ridge (Fig. 97*C*). Farther north the Elbing, Peabody, and Florence fields are on the west side of the ridge. Figure 97*D*, is a section across the State along the ridge, in which the numbers correspond to those of wells shown in Fig. 97*A*. Figure 97*E*, is a section across the ridge, in which the letters correspond to those of wells shown in Fig. 97*A*. The beds were laid down unconformably above the granite, and according to Moore the undulations in the beds are due to the settling or compacting of beds, the shrinking being greatest in the troughs where the beds were thickest.

The structural features are in general similar to those of the Oklahoma fields. The principal fields are shown in Fig. 98.

In the Peru region, lying mainly in Chautauqua County, but extending eastward into the western part of Montgomery County, oil is accumulated on a great structural terrace where the beds lie practically flat. For 25 miles down the dip the rocks dip 4 feet to the mile. West of this terrace for 25 miles the dip is about 50 feet to the mile, and east of it for 25 miles it is about 30 feet to the mile.

In the Independence quadrangle, Montgomery County, which lies just east of the Peru pool, between Independence and Coffeyville, there is an extensive area yielding oil and gas which is situated on the crest and well down the flanks of a gentle anticlinal fold. In Wilson County (Fredonia pool) and in Woodson County, to the north, gas and some oil are found on subordinate folds that rise not more than 50 feet above the general plane of the monocline. In the Iola quadrangle, Allen and Neosho Counties, accumulations occur on the monocline in gentle structural ravines and terraces with axes that strike approximately with the beds. In the Iola and La Harpe field, in northern Allen County, there is a low anticline or terrace about 8 miles wide.

[1] Moore, R. C.: The Relation of the Buried Granite in Kansas to Oil Production. Am. Assoc. Petr. Geol. *Bull.*, vol. 4, No. 3, pp. 255–261, 1920.

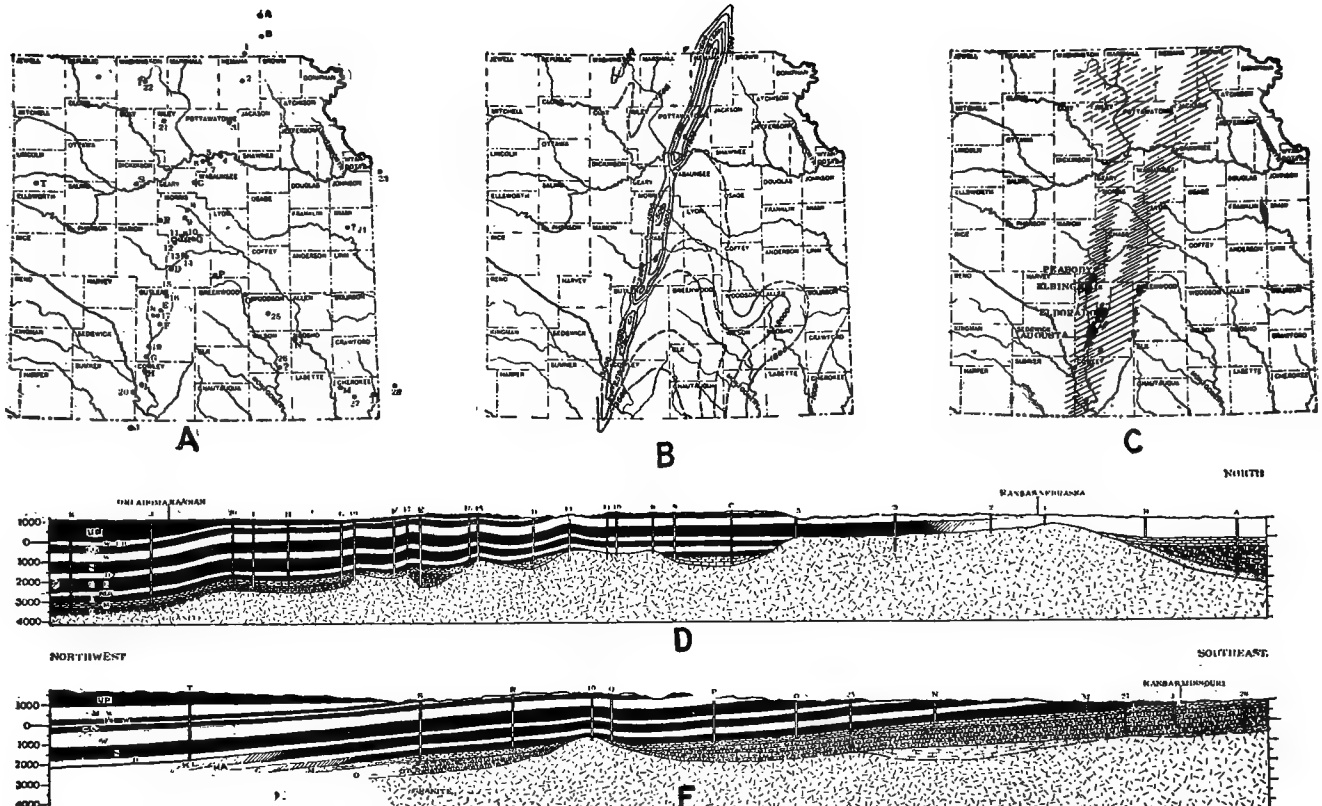


FIG. 97.—Maps and sections of eastern Kansas. In *A* wells encountering granite are lettered and other deep wells are numbered. *B* is a contour map of the buried granite ridge and shows the elevation of the top of the granite with reference to sea level. *C* shows oil fields (black) near the granite ridge and most promising area (shaded). *D* is a geologic section from north to south along the ridge and *E* is one from southeast to northwest across the ridge. Geologic formations: *O*—Ordovician; *M*—Mississippian; *C*—Cherokee; *Ma*—Marmaton; *KL*—Kansas City Lansing; *D*—Douglas; *S*—Shawnee; *W*—Wabansee; *CG*—Council Grove; *WR*—Wreford to Fort Riley; *UP*—Upper Permian. (*All are after Moore.*)

In the Eldorado and Augusta fields, Butler County, as already noted the oil and gas have accumulated in well-defined domes.

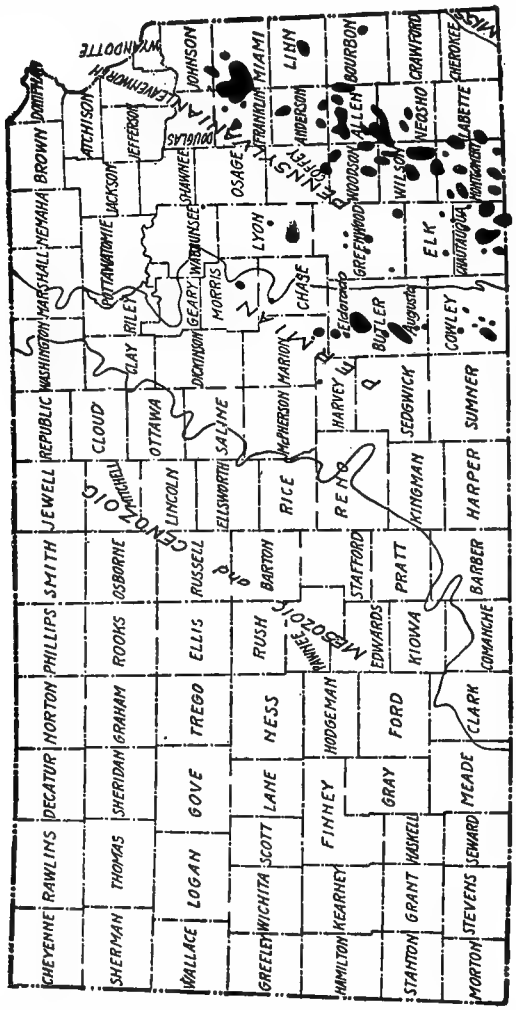


FIG. 98.—Index map of Kansas showing principal oil and gas fields.

Missouri.—Small quantities of oil and gas have been produced near Kansas City, Missouri, in Cass and Jackson counties. The producing strata are of Pennsylvanian age and dip northwest at low angles.[1] Southwest of Belton there is a small area of com-

[1] WILSON, M. E.: Oil and Gas Possibilities in the Belton Area, Mo. Bureau of Geol. and Mines, 1918.

plicated faulting. In several wells sunk to depths of about 400 feet heavy lubricating oil has been encountered.

Red River Region, Oklahoma and Texas.—The Red River region of southern Oklahoma and northern Texas (Fig. 99) includes parts or all of Carter, Love, Stephens, Jefferson, Cotton, and Comanche Counties, Oklahoma, and Clay, Wichita, and Wilbarger Counties, Texas. The Red River oil and gas pools include the Healdton, Fox, Graham, Loco, Duncan, and Lawton pools in Oklahoma, and the Electra, Burkburnett, and Petrolia fields of Texas. In this region, there is an embayment in the Permian outcrop south of the Arbuckle Mountains near the Red River. In the region of this embayment there is a great synclinal trough. The

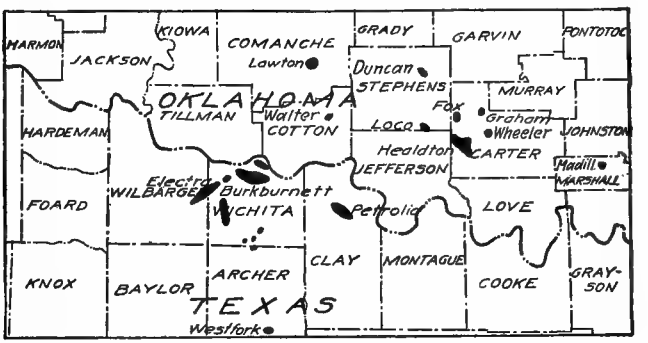


FIG. 99.—Index map of Red River region, Oklahoma and Texas.

beds dip southward from the Arbuckle Mountains and northwestward from the Llano uplift, in the region south of the Red River. The axis of the syncline plunges west. Superimposed on the larger synclinal basin and probably crossing it, is the great Red River zone of deformation,[1] which here has been identified, mainly by drilling. It extends along Red River and through counties that border the river for over 100 miles. This great uplift is probably of pre-Pennsylvanian age, according to Hager, who states that minor anticlines and domes such as those that exist at Electra and Petrolia, are due to movements of readjustment along old lines of stress in highly folded Ordovician rocks beneath.

[1] HAGER, LEE: Red River Uplift Has Another Angle. *Oil and Gas Jour.*, vol. 18, pp. 64–65, 1919.

Healdton, Okla.,[1] (Fig. 100) lies about 12 miles to the south of the Arbuckle-Wichita uplift. Petroleum was discovered here in 1913, and the field was developed within three years to one of the most productive fields in Oklahoma. The rocks at the surface are Permian Red Beds. From the surface to a depth of 600 to 950 feet the strata are principally shales, with a few water-bearing sandstones. Below these beds is a zone 250 feet thick which contains four or more petroliferous sands separated by beds of shale. Most of the oil produced in 1915 came from sands 800 to 1,150 feet deep. The higher petroliferous strata are classified as Permian by Wegemann and Heald,[2] and also by Aurin.[3] Powers, however, classes them as Pennsylvanian. The deeper oil-bearing strata are Pennsylvanian.

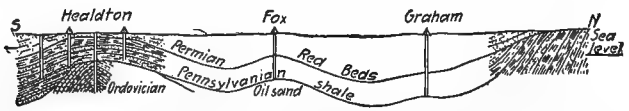


FIG. 100.—Cross-section of the Healdton field, Fox and Wheeler anticlines, Oklahoma, showing the relation of the buried Healdton Hills composed of Ordovician strata to the overlying Pennsylvanian and Permian strata. Length of section 21 miles. (*After Powers.*)

Structurally the field is an anticline on which several small domes are superimposed. The oil has accumulated at the top of the anticline, on the domes, and in the small structural depressions between them. On the flanks of the fold the beds carry salt water.

The productive pools of Wichita County, Texas, include Burkburnet, Electra, Fowlkes, and Iowa Park. These pools are in areas of Permian rocks, below which are strata of Pennsylvanian age.

The Electra field[4] is in the western part of Wichita County

[1] WEGEMANN, C. H., and HEALD, K. C.: The Healdton Oil Field, Carter County, Oklahoma. U. S. Geol. Survey *Bull.* 621, pp. 13–30, 1915.

POWERS, SIDNEY: The Healdton Oil Field, Oklahoma. *Econ. Geol.*, vol. 12, pp. 594–606, 1917; Age of the Oil in Oklahoma Fields. Am. Inst. Min. Eng. *Bull.* 113, p. 1982, 1917.

SHANNON, C. W., and others: Petroleum and Natural Gas in Oklahoma. Okla. Geol. Survey *Bull.* 19, part 2, pp. 79–101.

[2] *Op. cit.*, p. 24.

[3] SHANNON, C. W., and others: *Op. cit.*, insert table.

[4] UDDEN, J. A.: A Reconnaissance Report on the Geology of the Oil and Gas Fields of Wichita and Clay Counties, Tex. Tex. University *Bull.* 246, 1912.

near the Oklahoma line. The first reported occurrence of oil in this field was in a well dug in 1900 for water, north of what was then Beaver station; this well found oil at 147 feet. South of the station another well found a little oil at 205 feet. Since that date the area has been developed into a steadily productive field, yielding oil of high grade. The outcropping rocks are of Permian age, probably near the base of the Permian. The strata consist of shale and sandstone, with some limestone beds, and are referred to the Albany-Wichita. Below the Permian beds are Pennsylvanian shale, clay, and sandstone, with thin beds of limestone.

Oil and gas are found in the Permian, in the Pennyslvanian, and possibly in the Mississippian. The structure of the district is that of a broad anticline with a wide, nearly flat crest.

Burkburnet, which lies northeast of Electra, is one of the most productive fields in the Mid-Continent region. It is said to lie on a broad anticline, which at some places is probably complicated by faulting. It produces oil of good grade, rich in gasoline. A small part of the oil comes from beds that have been correlated with the Permian. The remainder is derived from deeper beds.[1] In 1916 and later many wells yielding from 1,000 to 2,000 barrels a day in flush production were encountered between 1,700 and 2,000 feet.

The Petrolia field[2] is in the northern part of Clay County, 12 miles north of Henrietta. The outcropping rocks are Red Beds of the Wichita formation and consist of shales and sandstones. These beds overlie the Cisco shale, of the Pennsylvanian, which consists of sandstones, clays, and shales and contains the oil and gas sands. As shown by Udden and Phillips,[3] the structure is anticlinal. There are three principal sands yielding gas or oil and gas. The average original pressure was 725 pounds to the square inch. Although the field has produced principally gas it has yielded also over 3,000,000 barrels of oil. The oil is light and of good grade.

North Central Texas Fields.—The oil fields that lie entirely or partly in Texas are grouped as follows:

[1] HAGER, LEE: Red River Uplift Has Another Angle. *Oil and Gas Jour.*, vol. 18, pp. 64–65, 1919.

[2] SHAW, E. W.: Gas in the Area North and West of Fort Worth. U. S. Geol. Survey *Bull.* 629, pp. 1–75, 1916.

[3] UDDEN, J. A., and PHILLIPS, D. MCN.: A Reconnaissance Report on the Geology of the Oil and Gas Fields of Wichita and Clay Counties, Texas. Tex. University *Bull.* 246, 1912.

1. Red River region of northern Texas and southern Oklahoma.
2. North-central Texas fields, including Strawn, Allen, Duke, Caddo, Veale, Ranger, Breckenridge, Moran, Santa Anna, Brownwood, Trickham, Lohn, and others.
3. Fields in the Upper Cretaceous area east of the Balcones fault.
4. Western part of Sabine uplift in Texas and Louisiana.
5. Gulf coast fields.

The Red River region has been described (p. 159).

The north-central Texas fields[1] as developed in 1919 were practically coextensive with the belt of Pennsylvanian strata that extends northward from the Llano-Burnet uplift nearly to the Oklahoma line. These strata generally dip north west at low angles. Toward the east the Pennsylvanian is overlapped by the Trinity sand (Lower Cretaceous). Toward the west it is overlain by Permian strata. Below the Pennsylvanian is found the Bend series, which crops out in the Llano uplift but which is buried to the north. This series is unconformable with the overlying Pennsylvanian.

The dominant structural feature in the northern Texas field is a monocline dipping northward from the Llano uplift at about 25 feet to the mile. On this monocline is superimposed a low arch that extends from the Llano-Burnet region northward about 150 miles. This arch is more accentuated in the Bend series than in the overlying rocks, and has been designated the Bend arch. On this arch oil is accumulated in Mississippian and Pennsylvanian sands, in the Ranger, Desdemona (Duke-Knowles), and other pools.

At numerous places small wrinkles are found on the arch. Oil is concentrated below these wrinkles, especially below small open

[1] Adams, G. I.: Oil and Gas fields of Western Interior and Northern Texas Coal Measures. U. S. Survey *Bull.* 184, pp. 1–64, 1901.

Hill, R. T.: Geography and Geology of Black and Grand Prairies Texas. U. S. Geol. Survey *Twenty-first Ann. Rept.*, part 7, pp. 1–666, 1900.

Wegemann, C. H.: A Reconnaissance in Palo Pinto County, Texas. U. S. Geol. Survey *Bull.* 621, pp. 51–59, 1912.

Matteson, W. G.: A Review of the Development in the New Central Texas Oil Fields During 1918. *Econ. Geol.* vol. 14, pp. 95–146, 1919.

Hager, Dorsey: Geology of the Oil Fields of North-Central Texas. Am. Inst. Min. Eng. *Trans.* vol. 61, pp. 520–531, 1919.

Pratt, W. E.: Geology of the Oil Fields of North Central Texas (discussion). Am. Inst. Min. Eng. *Trans.* vol. 61, pp. 530–531, 1919.

anticlines. Few of the anticlines close at the surface, but the folds become more acute below the surface, so that certain folds which do not close at the surface close in depth. Moreover, owing to the unconformities present, some folds found in depth may not be expressed at the surface, although those found at the surface are generally expressed in depth.

Oil is obtained at eight horizons in north-central Texas. Some of the sands are probably lenticular, and different sands are productive in different wells. The sands as a rule are thin. Most of the wells yield gas, and in many of them the oil issues under high pressure. Salt water has been encountered in several wells. The initial production of many wells is large, and the oil is of high grade.

Owing partly to the escape of gas in wells, the pressure has declined in this region. The absence of sufficient gas to force the oil into the borings has resulted in an exceptionally rapid decline in the yield of oil wells in some of the fields that were originally highly productive.

Balcones Fault Region.—East of the north Texas fields is the Balcones fault zone, which extends from Hunt County, in northeastern Texas, southwestward to Bexar County, about 300 miles. The rocks involved are strata of the Lower and Upper Cretaceous series. In the zone of deformation east of the fault there are small folds in which oil or gas or both are concentrated. In this zone is the Corsicana field, which embraces the Burke, Eden, Powell, and Chatfield pools and other small pools near by. South of the Corsicana field, in Limestone County, is the Mexia-Groesbeck gas field, west of which, in McLennan County, is the South Bosque field, and south of that the Thrall and Elgin fields. About 100 miles southwest of Elgin is a small field near San Antonio. In the Balcones region oil and gas are found on anticlines and terraces in the Nacatoch sand and Woodbine sand of Upper Cretaceous age. Large flowing wells have recently been brought in in the Mexia-Groesbeck field.

Northwestern Louisiana and Northeastern Texas.—Northwestern Louisiana and northeastern Texas are covered with Tertiary and Quaternary deposits. The rocks at the surface generally dip at low angles away from the older rocks that occur farther north. Superimposed on the monocline are long zones of deformation marked by faulting or by folding (Fig. 101). One of these zones of deformation is the Red River fault zone, which in northwestern Louisiana is probably represented by a sharp

GENERALIZED SECTION OF FORMATIONS IN THE CORSICANA OIL AND GAS FIELD EAST OF BALCONES FAULT, TEXAS

(After Matson and Hopkins)

System	Series	Group	Formation	Thickness (feet)	Character
Quaternary	Recent				Alluvial deposits along streams.
	Pleistocene				Terrace deposits.
Tertiary	Eocene		Midway formation	250–500	Micaceous sandy clays, fine argillaceous sands, and limestone concretions.
Cretaceous	Gulf (Upper Cretaceous)		Navarro formation	1,800–2,000	Light to dark gray calcareous clay, sandy clay, and fine lenticular beds of sand.
			Taylor marl		Massive calcareous clay marl, little sand, and glauconite.
			Austin chalk	400–500	Gray to white chalky limestone containing some hard beds.
			Eagle Ford shale	300–400	Light to dark colored shale or clay and thinly laminated impure limestone.
			Woodbine sand	400–450	Sand, sandy lignitic clay, sandstone, ferruginous sand, and clay.
	Comanche (Lower Cretaceous)	Washita	Denison formation	150–200	Clay and limestone.
			Fort Worth limestone	25–75	Alternating beds of limestone and marl.
			Preston formation	50–100	Calcareous laminated clays and impure limestone.
		Fredericksburg	Edwards limestone	300–400	White chalky limestones, Variously indurated, and in places fine arenaceous beds.
			Comanche Peak limestone		
			Walnut clay	100–200	Calcareous clays and impure marly and chalky limestones.
		Trinity	Paluxy sand	125–200	Fine-grained sand and lenticular beds of clay.
			Glen Rose limestone	300–500	Impure limestone, marl, and calcareous shales.
			Travis Peak sand	250 ±	Conglomerate, sand, sandstone, shales, and impure limestones.

flexure that dips north. As mapped by Veatch this zone extends to the Mississippi River.

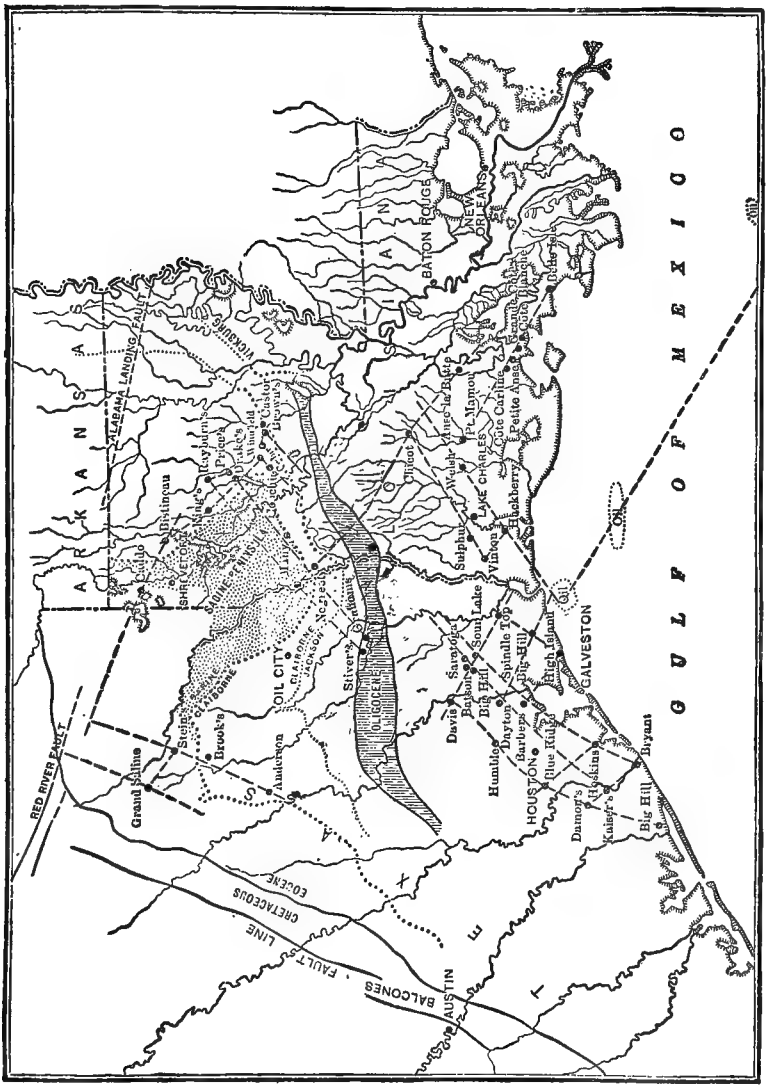


FIG. 101.—Map showing probable structural lines in Mississippi embayment region. (*After Harris.*)

The Angelina flexure extends from Angelina County, Texas, northeastward into Louisiana and possibly to the Mississippi River. Along the flexure the rocks dip to the southeast at a high

angle. Between the Red River zone of deformation and the Angelina flexure lies a great, broad dome—the Sabine uplift (Fig. 102). From this dome the rocks dip northeast along the Red River zone of deformation, east to the Mississippi River, southeast along the Angelina flexure, and west in eastern Texas.

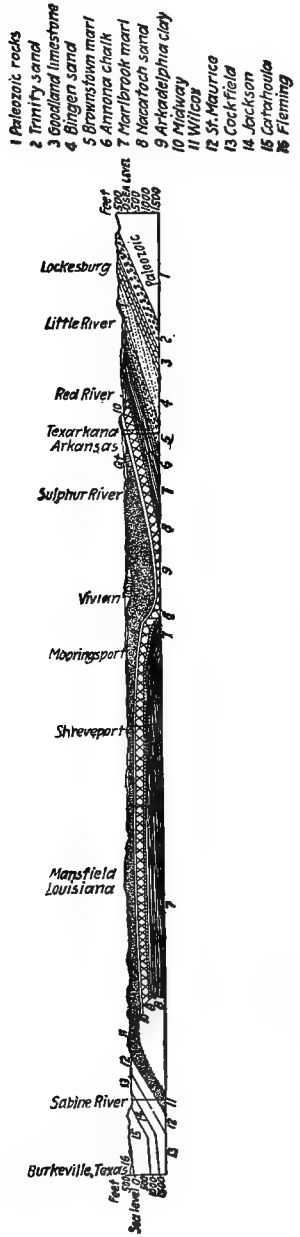


FIG. 102.—Section across portions of Arkansas, Texas and Louisiana looking west. (*After Harris.*)

In this region deformation has taken place in late geologic time. In the Wilcox formation, of the Eocene, the rocks locally dip 10° or more.

Contour maps of the structure of the Sabine uplift show that the dome has an undulating crest. Three anticlinal axes are noteworthy. These are approximately parallel and strike northeast. On the north one are the oil fields of Caddo Lake. The central axis lies near Shreveport and extends northeastward, passing through the Homer field. South of this is a third axis which is developed in the De Soto-Red River field. It practically coincides with the Gusher Bend fault of that field. High points along the crests of these folds are essentially in line, suggesting a second series of folds striking northwestward across the axes of the northeast folds.

The fields on the Sabine uplift that yield oil or gas or both include the Caddo, Shreveport, De Soto-Red River (Bull Bayou), Elm Grove, Pelican, Homer, Monroe, and others (see Fig. 103). The Upper Cretaceous section is nearly

the same as in the Balcones fault region. The oil and gas or both are found in the Nacatoch sand, the Annona chalk, the Blossom sand member of the Eagle Ford clay, and the Woodbine sand, all Upper Cretaceous.

Gulf Coast Fields of Texas and Louisiana.—Eastern Texas and Louisiana are underlain by Mesozoic and Cenozoic rocks, which crop out as broad belts in which the younger rocks lie successively nearer the sea. The younger beds extend farther north in the region of the Mississippi River than east or west of it. Structurally the region has been characterized as a gently pitching trough with its axis lying along the river. The beds in general dip at very low angles, though locally they are sharply flexed.[1]

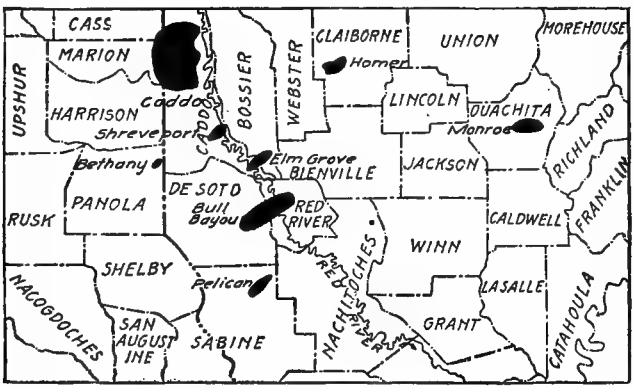


FIG. 103.—Sketch map showing oil and gas fields in northern Louisiana and northeastern Texas. Bethany, Shreveport, Elm Grove and Monroe are gas fields. Caddo, Homer, Bull Bayou, and Pelican are oil fields.

The country is approximately flat, and details of structure are derived principally from drill holes. At many places low mounds or hills rise above the generally level plain. On some of these

[1] HARRIS, G. D.: Oil and Gas in Louisiana, with a Brief Summary of Their Occurrence in Adjacent States. U. S. Geol. Survey *Bull.* 429, 1910.

DEUSSEN, ALEXANDER: Geology and Underground Waters of the Southeastern Part of the Texas Coastal Plain. U. S. Geol. Survey *Water-Supply Paper* 335, 1914.

VEATCH, A. C.: Geology and Underground Water Resources of Northern Louisiana and Southern Arkansas. U. S. Geol. Survey *Prof. Paper* 46, 1906.

KENNEDY, WILLIAM: Coastal Salt Domes. Southwestern Assoc. Pet. Geol. *Bull.*, vol. 1, pp. 34–59, 1917.

there are small lakes from which gas bubbles escape. Sulphur, sulphur dioxide, sulphuric acid, saline water, gas, oil, asphalt, or "paraffin dirt" are sought for as evidences of oil-bearing areas. These indications are found also at some places where there is no mound or rise of the land. Drilling has shown that cores of salt with petroliferous beds underlie many of the mounds or the other places where one or more of the indications noted above are present. Among the most productive domes of this region are Spindletop (Fig. 104), Sour Lake, Saratoga, Batson, Dayton, Damon Mound, Goose Creek, and West Columbia, in Texas, and Welch, Evangeline (Jennings), and New Iberia, in Louisiana. In general the oil and gas are found in sharp structural domes.

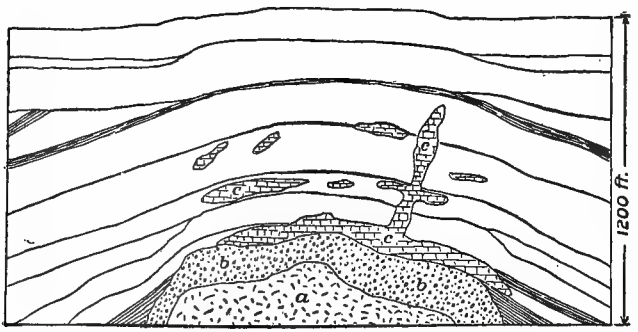


FIG. 104.—Section of Spindletop oil field, Texas. *a*, Rock salt; *b*, gypsum; *c*, limestone. (*After Lee Hager.*)

The oil is heavy and is used chiefly for fuel. The origin of the domes has been a subject for much discussion. Harris believes that the crystallization of the salt cores has thrust the overlying beds upward. Others hold that the domes are simply sharp folds along lines of deformation.

Rocky Mountain Fields.—The most productive oil fields of the Rocky Mountain region are in Wyoming (Fig. 105), although oil has been produced in several districts in Montana and Colorado and is known to occur in New Mexico and Utah.

Wyoming.—The principal oil field of Wyoming (Fig. 105) is the Salt Creek field, about 40 miles north of Casper, which produces oil of good quality with a fairly high gasoline content. The field is a dome of Cretaceous rocks, and the oil is found in the Wall Creek sands (Upper Cretaceous, Colorado), which are covered by shales.

At the crest of the dome the first Wall Creek sand is reached at a depth of about 1,000 feet. This sand is about 125 feet thick and consists of medium-grained sandstone containing thin calcareous beds and lenses and layers of sandy shale.

The distribution of the oil about the Salt Creek dome is unusually regular. The line marking the contact of the oil pool with the water that occupies the sand on the flanks of the fold below the oil varies only about 150 feet in elevation in the entire circuit of the dome[1] (see Fig. 69, p. 122).

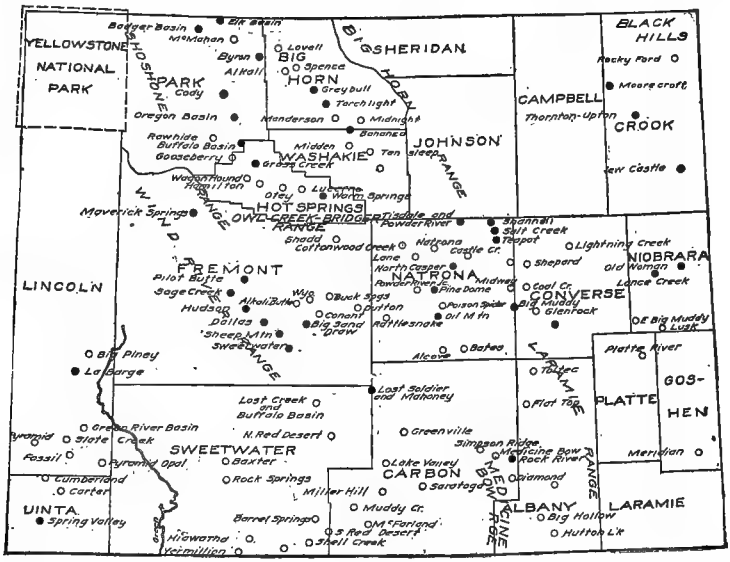


FIG. 105.—Map of Wyoming showing position of certain oil and gas pools (black dots) and prospects (circles).

The Big Muddy dome[2] is about 15 miles east of Caspar. Oil is obtained on an anticline from the Wall Creek and other sands in the Colorado.

Near Lander[3] several small domes are superimposed on a foothill fold of the Wind River Mountains. In these domes a heavy oil is found in the Embar limestone of the Carboniferous.

[1] WEGEMANN, C. H.: The Salt Creek Oil Field, Wyoming. U. S. Geol. Survey *Bull.* 670, p. 27, 1917.

[2] BARNETT, V. H.: Possibilities of Oil in the Big Muddy Dome, Converse and Natrona Counties, Wyoming. U. S. Geol. Survey *Bull.* 581, pp. 105–117, 1915.

[3] WOODRUFF, E. G.: The Lander Oil Field, Fremont County, Wyoming. U. S. Geol. Survey *Bull.* 452, pp. 1–36, 1911.

FORMATIONS IN SALT CREEK OIL FIELD, WYOMING
(After Wegemann)

System	Series	Group	Formation	Character	Thickness (feet)
Tertiary	Eocene		Wasatch formation.	Yellow sandstone, gray shale and coal.	2,400
			Fort Union formation.	Fine-grained bluish-white sandstone and gray shale.	2,000
Tertiary (?)	(?)		Lance formation.	Concretionary buff sandstone and shale.	3,200
Cretaceous	Upper Cretaceous	Montana	Lewis shale with thick sandstone at top and another sandstone in middle.	Sandstone, white to brown, and gray shale.	1,400
			Mesaverde formation, including Parkman, and Teapot sandstone members.	Shale, sandstone, thin coal beds.	845
			Steele shale, including Shannon sandstone member. Carries oil.	Buff sandstone and gray shale.	2,275
		Colorado	Niobrara shale.	Light-colored shale, in parts somewhat arenaceous.	735
			Benton shale	Dark shale.	220
			Benton shale: Wall Creek sandstone member and lower sands with interbedded shale. Cary oil.	Buff to white sandstone and gray shale.	685
			Benton shale	Dark shale.	250
			Benton shale: Mowry shale member.	Firm slaty shale, usually forming escarpment. Weathers light gray and bears fish scales.	280
			Benton shale	Dark shale.	205
	Lower Cretaceous		Cloverly formation.	Thin sandstone and dark shale.	150
				Conglomerate.	
Cretaceous (?)	(?)		Morrison formation.	Variegated shale with several sandstone beds.	250
Jurassic	Upper Jurassic		Sundance formation.	Shale, limestone, and sandstone.	150

The Pilot Butte field,[1] 26 miles north of Lander, is on an elongated dome. The oil produced there has a paraffin base and

[1] ZIEGLER, VICTOR: The Pilot Butte Oil Field, Fremont County, Wyoming. Wyo. Geol. Survey *Bull.* 13, p. 143, 1916.

is obtained from a Cretaceous sandstone about 1,500 feet above the base of the Pierre.

In northeastern Wyoming, on the flanks of the Black Hills, which constitute a great domical uplift, oil is found in small domes and in sealed beds that show no closed folds, in the sands of the Colorado (Upper Cretaceous). Among the fields of eastern Wyoming are those of Upton-Thornton, Newcastle, Moorcroft, Mule Creek, and Buck Creek.

In the Big Horn Basin Northwest Wyoming oil or gas is found in four or more sands in the Colorado. Among the most productive fields are the Grass Creek, Graybull, Torchlight, Buffalo Basin, Oregon Basin, Elk Basin, and Shoshone fields. The Big Horn Basin is almost completely surrounded by mountains. Near the mountains there are two circular chains of anticlines and domes,[1] one inside the other (Fig. 106). The inner circle has yielded almost the entire production of the area. All of the producing folds are elongated domes, or anticlines plunging at both ends. Their axes are rudely parallel to the axes of the mountain ranges, which almost encircle the basin. The domes and anticlines have large closures; that of the Grass Creek anticline, the most productive in the basin, is nearly 3,000 feet. Many of the oil-bearing folds are faulted, but moderate amounts of faulting do not seem to influence accumulation adversely in this region. For a productive region that is so much faulted, surface indications of oil are not numerous, although several oil seeps have been found. The oil-bearing strata are all or nearly all marine. Salt water is found in many of the folds, but in some of them it is not very salty. The water below the oil on both limbs of the Grass Creek anticline is neither sulphurous nor very salty, but is somewhat alkaline.

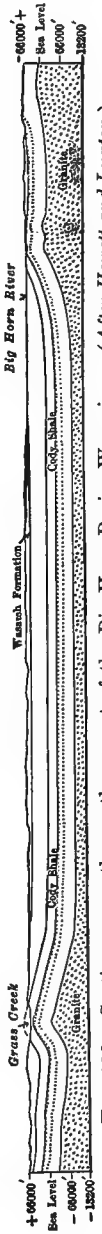


FIG. 106.—Section across the southern part of the Big Horn Basin, Wyoming. (*After Hewett and Lupton.*)

[1] HEWETT, D. F., and LUPTON, C. T.: Anticlines in the Southern Part of the Big Horn Basin, Wyoming. U. S. Geol. Survey *Bull.* 656, 1917.

Presumably the surface water has entered the oil-bearing sands down the dips of the beds and along faults and either diluted the water that had been stored in the sands or swept it out.

Montana.—Montana had produced practically no oil until 1919 except from Elk Basin, which is in the Big Horn Basin, partly in Wyoming and partly in Montana.

Commercial quantities of gas have been found very near Baker and Glendive, Dawson County. Two oil wells were sunk in Devil's Basin,[1] near Roundup, in 1919. One of them, the Van Duzen well, yielded a heavy black oil of 23° Baumé. In eastern Fergus County, near Mosby, on the Cat Creek[2] dome

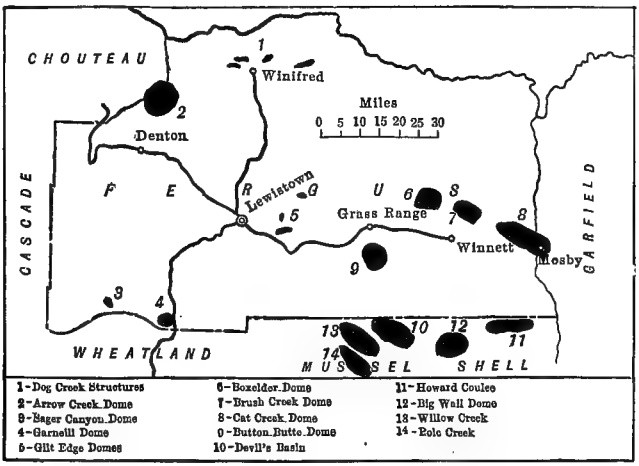


FIG. 107.—Sketch of Fergus County and parts of adjoining counties, Montana, showing positions of domes, oil fields and prospects. (*After Freeman.*)

(Fig. 107), three wells were brought in during 1920. These yielded a high-gravity oil. The Soap Creek field,[3] Hardin County, contains several anticlines on the northeast slope of the Bighorn uplift. A heavy oil is produced from the Amsden (Pennsylvanian) Limestone.

[1] BOWEN, C. F.: Coal Discovered in a Reconnaissance Survey Between Musselshell and Judith, Montana. U. S. Geol. Survey *Bull.* 541, part 2, pp. 329–337, 1914.

[2] FREEMAN, O. W.: Oil Fields in Central Montana. *Eng. and Min. Jour.*, vol. 109. pp. 936–938, 1920.

[3] THOM, W. T., JR. and MOULTON, G. F.: The Soap Creek Oil Field. Montana *Press Notice,* U. S. Geol. Survey, 1921.

Colorado.—In Colorado the principal producing areas are the Florence and Boulder fields, in both of which the oil comes from the Pierre shale. In the San Juan field oil has been found in the Goodridge formation, near the top of the Pennsylvanian. In the De Beque field oil is found probably in the Mesaverde or at the base of the Wasatch. In the Rangely district, Rio Blanco County, some oil is found in the Mancos formation. At Urado, near Black Dragon station, near the western boundary of Rio Blanco County, a little oil comes from a horizon not far below the base of the Green River oil shales. In the Florence field[1] the oil comes from fissures in the Pierre shale, and in the Boulder field from[2] sands or sandstones in the Pierre. In the northern part of the Boulder field oil is developed on an anticline.[3] The oil is of fair grade, that at Florence running 30° Baumé and that at Boulder being higher.

California.—The oil fields of California (Fig. 108) lie in a belt 225 miles long extending from the Coalinga district, in Fresno County, at the north, to the Puente Hills district, in Orange County, at the south. The fields in this belt, which are among the most prolific in the United States, produce mainly oils of medium to heavy grade, with asphaltic base. The rocks containing the oils are partly unconsolidated and in most of the oil-producing areas, are intensely deformed, so that the beds lie at high angles. In some of the districts the strata are overturned. Oil seeps are numerous, and asphalt beds cover wide areas.

Commercial quantities of petroleum are found in California in every important geologic formation from the Chico (Upper Cretaceous) to the Fernando (Pliocene) and also in the Quaternary deposits as tar springs and asphaltum. The principal formations of the oil fields, in order of age, are Jurassic or pre-Jurassic crystalline rocks; the Franciscan (probably late Jurassic); the Knoxville-Chico rocks (Cretaceous); the Tejon (Eocene); the Sespe (probably Oligocene); the Vaqueros and Monterey (lower Miocene); the Fernando or equivalent (largely upper Miocene

[1] WASHBURNE, C. W.: The Florence Oil Field, Colorado. U. S. Geol. Survey *Bull.* 381, pp. 517–544, 1910.

[2] FENNEMAN, N. M.: Geology of the Boulder District, Colorado. U. S. Geol. Survey *Bull.* 265, 1905.

[3] WASHBURNE, C. W.: Development in the Boulder Oil Field, Colorado. U. S. Geol. Survey *Bull.* 381, pp. 514–516, 1910.

and Pliocene); and the Quaternary. Commercial quantities of oil are found chiefly in the Miocene.[1]

The Coalinga[2] district is an area of Cretaceous and Tertiary strata, only slightly consolidated, closely folded, and not extensively faulted. The dominant structural feature is the monocline that dips eastward from the Coast Range to the valley. On this is developed the Coalinga anticline, and bordering it the

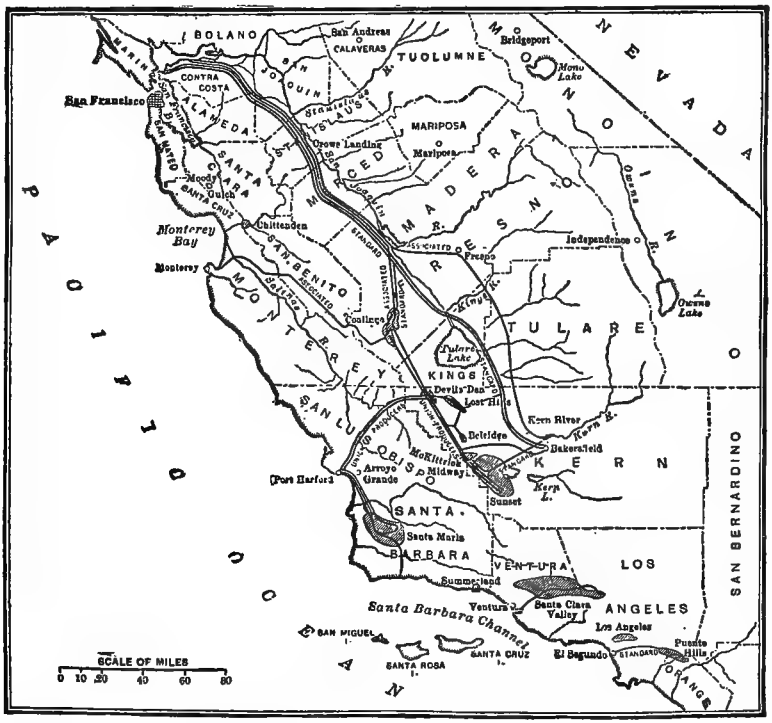


FIG. 108.—Sketch of part of California showing oil districts and pipe lines. (*After Arnold and Garfias.*)

Coalinga syncline and a great monoclinal area that forms the west limb of the syncline. The oil is found in sands, principally near the top of the anticline and on the monocline. The geologic formations are shown in Fig. 109.

[1] ARNOLD, RALPH and GARFIAS, V. R.: Geology and Technology of the California Oil Fields. Am. Inst. Min. Eng. *Bull.* 87, p. 405, 1914.

[2] ARNOLD, RALPH and ANDERSON, ROBERT: Geology and Oil Resources of the Coalinga District, California, with a Report on the Chemical and Physical Properties of the Oils by IRVING C. ALLEN. U. S. Geol. Survey *Bull.* 398, 1910.

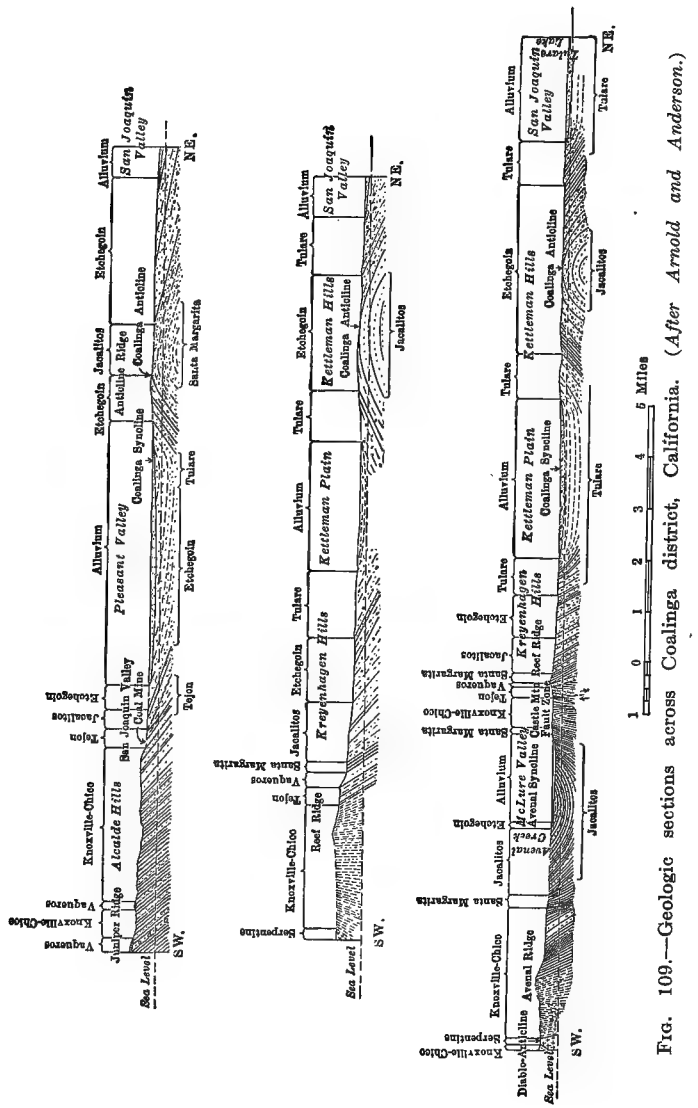


FIG. 109.—Geologic sections across Coalinga district, California. (*After Arnold and Anderson.*)

The McKittrick, Sunset, and Midway fields[1] are in Kern County, south of the Coalinga district. They lie on the east slope of the Temblor Range, which rises some 4,000 feet above the sea. The range is a great monocline dipping northeast, on which are developed many minor folds. On the southwest the Temblor Range is bordered by the great San Andreas fault zone, which has been traced from Point Arena, on the Pacific Coast north of San Francisco, for over 600 miles, nearly to Salton Sea.[2] The faulting and folding on the side of the range give in effect a huge anticlinorium, which is most clearly shown in the northwestern part of the area.

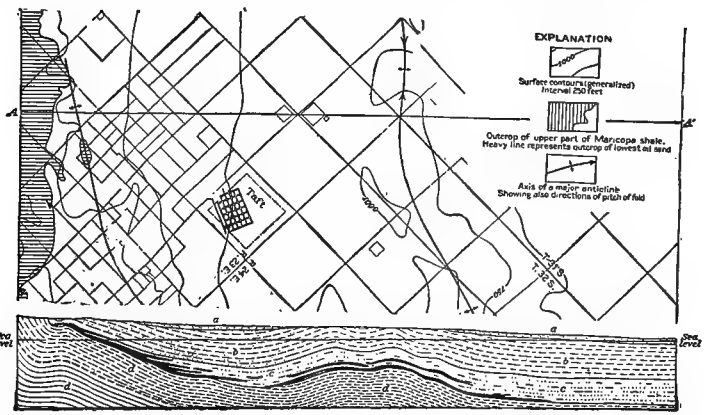


FIG. 110.—Upper figure is a plan of part of Sunset-Midway field, near Taft, Calif. Each large square is one square mile. Contour interval is 250 feet. The lower figure is a section on line *AA'*. *a*, Alluvium; *b*, Paso Robles ("Tulare") formation; *c*, Etchegoin formation (contains chief petroleum reservoirs of the district); *d*, Maricopa shale. (*After Pack.*)

The McKittrick field lies on the flanks of three complex folds subsidiary to the great northeastward-dipping monocline of the Temblor Range. Thrust faulting and overturning have so complicated the folding as to place the older beds locally above the younger.

The Sunset-Midway field (Fig. 110) has recently been described

[1] ARNOLD, RALPH and JOHNSON, H. R.: Preliminary Report on the McKittrick-Sunset Oil Region. U. S. Geol. Survey *Bull.* 406, 1910.

ARNOLD, RALPH and GARFIAS, V. R.: Geology and Technology of the California Oil Fields. Am. Inst. Min. Eng. *Bull.* 87, pp. 383–470, 1914.

[2] LAWSON, A. C.: Report of the Earthquake Investigation Committee on the California Earthquake of April 18, 1906. Carnegie Inst. Washington, *Pub.* 87, 1908.

by Pack[1] and Rogers.[2] The area covered in their reports overlaps the area mapped by Arnold and Johnson and extends farther southeast.

The oil-bearing beds in the late Tertiary sequence are coarse and fine sands that range in thickness from a few feet to a few hundred feet. These beds crop out in the foothills of the Temblor Range, and their line of outcrop marks the western limit of the main productive field. Toward the east the productive oil sands are buried progressively deeper beneath the surface. In the eastern part of the field the productive sands, which are usually 10 to 50 feet thick, are interspersed with barren beds of equal thickness through a section 600 to 800 feet thick.

The richest sands lie close to the contact with the diatomaceous shale. These oil-bearing beds are, however, not of the same age throughout the field, for the formation, of which they are a part, rests unconformably on the shale, and beds that abut against the shale in the western part of the field are younger than those against the shale in the eastern part.

The oil has evidently moved chiefly through the lowest part of the formation that rests upon the diatomaceous shale, as these beds are fairly porous and offer less resistance to the movement of the oil than the shale. The movement is therefore chiefly parallel to the plane of unconformity—that is, to the top of the shale. Near the outcrop, either by fractionation or by reaction with alkaline water, the oil becomes very viscous and seals the beds through which the oil is moving.

The Kern River field, about 4 miles north of Bakersfield, is a low dome on which are minor folds. The field was discovered in 1900 and soon became one of the most productive in California. The oil is heavy (14° Baumé)and is used mainly for fuel and for road making. It is found in the Monterey and later Tertiary sands and conglomerate. Sands and gravels extend from the surface to varying depths, the maximum 200 feet. Beneath this there is usually a stratum of blue clay, which ranges in thickness from a few feet to 100 feet. This clay is impermeable to the waters which are present in the sands above. Below the clay

[1] PACK, R. W.: The Sunset-Midway Oil Field, California, part 1, Geology and Oil Resources. U. S. Geol. Survey *Prof. Paper* 116, pp. 1–179, 1920.

[2] ROGERS, G. S.: The Sunset-Midway Oil Field, California, part 2, Geochemical Relations of the Oil, Gas, and water. U. S. Geol. Survey *Prof. Paper* 117, pp. 1–103, 1919.

are sands and clays. The sands constitute the oil reservoirs of the field. In a great many wells 200 or 300 feet of oil-bearing sand is found. Below the oil sands is another clay.

The Santa Clara district,[1] in Ventura and Los Angeles counties, is the oldest oil-producing area in California. The rocks of the region are Tertiary and Quaternary, except a small area of pre-Cretaceous granite and gneiss at the southeast corner. Oil is found in the Oligocene and Miocene and ranges from 11° to 37° Baumé.

The general structure in this district is dominated by an overturned anticline, which makes up the mountain range to the north parallel to the productive oil fields. The local structure affecting the accumulation of oil in any particular region is very complicated, sharp folds, faults, cross folds, and overturned folds being common.

A noteworthy feature of the district is the red shale associated with the oil formation, which has been burned red to a considerable depth by fire, evidently caused by combustion of the oil it contained.

The Summerland[2] district is in Santa Barbara County, about 80 miles northwest of Los Angeles. The field is of small economic importance. The beds dip south from the Arroyo Parida fault, which is also the crest of an anticline. Small folds are developed on the south limb of this anticline in the region of the oil wells. The Monterey has been eroded from the top of the anticline. Resting unconformably on the truncated edges of the Monterey are the Fernando beds which are steeply tilted.

The oil wells are put down on the terrace on which the town is situated, on the beach in front of this terrace, and on wharves that extend out into the ocean, some of them nearly a quarter of a mile. They range in depth from 100 to more than 600 feet; the deepest are those on the wharves. The oil is obtained from sands which alternate with clay beds in the Fernando formation.

The Santa Maria oil district,[3] comprising the Santa Maria,

[1] ELDRIDGE, G. H.: The Santa Clara Valley Oil District, Southern California. U. S. Geol. Survey *Bull.* 309, 1907.

ARNOLD, RALPH, and GARFIAS, V. R.: Geology and Technology of the California Oil Fields. Am. Inst. Min. Eng. *Bull.* 87, pp. 447–452, 1914.

[2] ARNOLD, RALPH: Geology and Oil Resources of the Summerland District, California. U. S. Geol. Survey *Bull.* 321, p. 21, 1907.

[3] ARNOLD, RALPH and ANDERSON, ROBERT: Preliminary Report on the Santa Maria Oil District. U. S. Geol. Survey *Bull.* 317, 1907.

Lompoc, and Arroyo Grande fields, lies in northern Santa Barbara County, and southern San Luis Obispo County. The area is occupied mainly by sedimentary rocks thrown into long and moderately gentle folds that trend principally northwest and west. Several faults of small displacement trend nearly parallel to the folds. The rocks present in the petroliferous region include the Monterey (middle Miocene) diatomaceous and clay shale, limestone, and volcanic ash; Fernando (Miocene-Pliocene-Pleistocene) conglomerate, sandstone, and shale; and Quaternary gravel, sand, clay, and alluvium. At the surface there are oil and tar seeps, asphalt, and bituminous shale.

The wells range in depth from 1,500 to more than 4,000 feet. In the Santa Maria and Lompoc fields they obtain their oil from zones of fractured shale or sandy layers in the lower portion of the Monterey shale. The gravity of the oil ranges from 19° to 35° Baumé. In the Arroyo Grande field the oil comes from sandstone at the base of the Fernando and has a gravity of 14°.

The Los Angeles city field[1] extends westward for 6 miles from a point about 4½ miles west of the business center of Los Angeles. The wells are from 500 to 1,200 feet deep, and the gravity of the oil is from 12° to 19° Baumé. The wells are small producers and are pumped. The Salt Lake field is a few miles west of the city field. The wells are between 1,200 and 3,000 feet deep, and the average gravity of the oil is between 16° and 18° Baumé. Considerable gas under strong pressure accompanies the oil, which causes the wells to gush during their early life.

Enormous deposits of brea or impure asphalt have formed along the outcrop of the upper Puente sand and in the wash above the oil sand. Some of the oil has apparently risen through cracks in the shaly beds above the oil sand and has escaped to the surface.

The City field is developed in strata at the top of the Monterey and possibly the base of the Fernando formation, on the south limb of the Elysian Park anticline. The trend of the productive belt, however, instead of conforming to the axis of the main fold, follows the strike of the formations on the south side of a divergent subordinate line of disturbance and has a direc-

[1] ELDRIDGE, G. H. and ARNOLD, RALPH: The Santa Clara Valley, Puente Hills, and Los Angeles Oil Districts, California. U. S. Geol. Survey *Bull.* 309, p. 138, 1907.

tion about east. The oil appears to have accumulated in the sands of the southern limb of the anticline just below the point where the steeply dipping beds bend toward the horizontal before passing over the axis of the fold. The structure in the Salt Lake field appears to be that of a minor flexure on the flanks of the fold along whose southern limb the other Los Angeles fields are situated (Figs. 111–112).

The Puente Hills,[1] about 12 miles southeast of Los Angeles, extend east-southeastward for about 22 miles. This region, which includes several oil fields, is one of the most persistent producers in the State. The oil is from 15° to 34° Baumé.

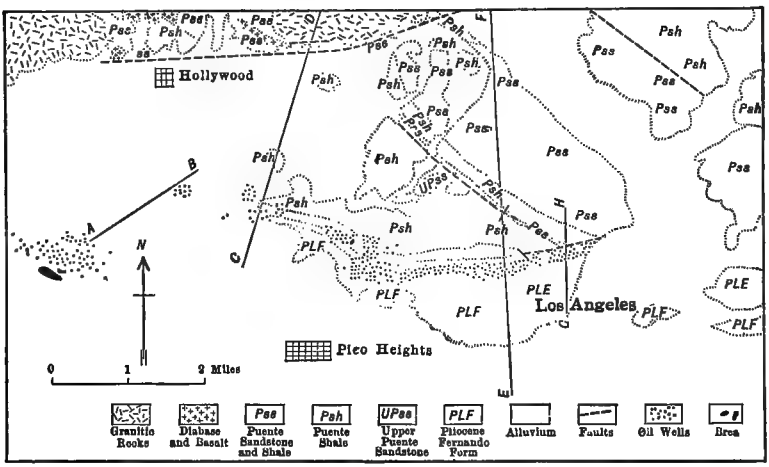


FIG. 111.—Sketch of part of Los Angeles oil field, California, showing position of certain wells and of sections shown in Fig. 112. (*Data from Eldridge and Arnold, U. S. Geol. Survey.*)

The dominant structural feature is an anticlinorium, in which the main fold trends N. 65° W. The axes of the greater anticlines are locally faulted. The oil fields lie in the zone of sharp crumpling and in proximity both to the trace of the fault and to a line of unconformity. Development in the Puente Hills region has been guided by the numerous seeps that occur along the belt of severely disturbed strata, but not all these seeps have proved reliable indications of large accumulations of oil.

[1] ELDRIDGE, G. H.: The Puente Hills Oil District, Southern California. U. S. Geol. Survey *Bull.* 309, pp. 102–137, 1907.

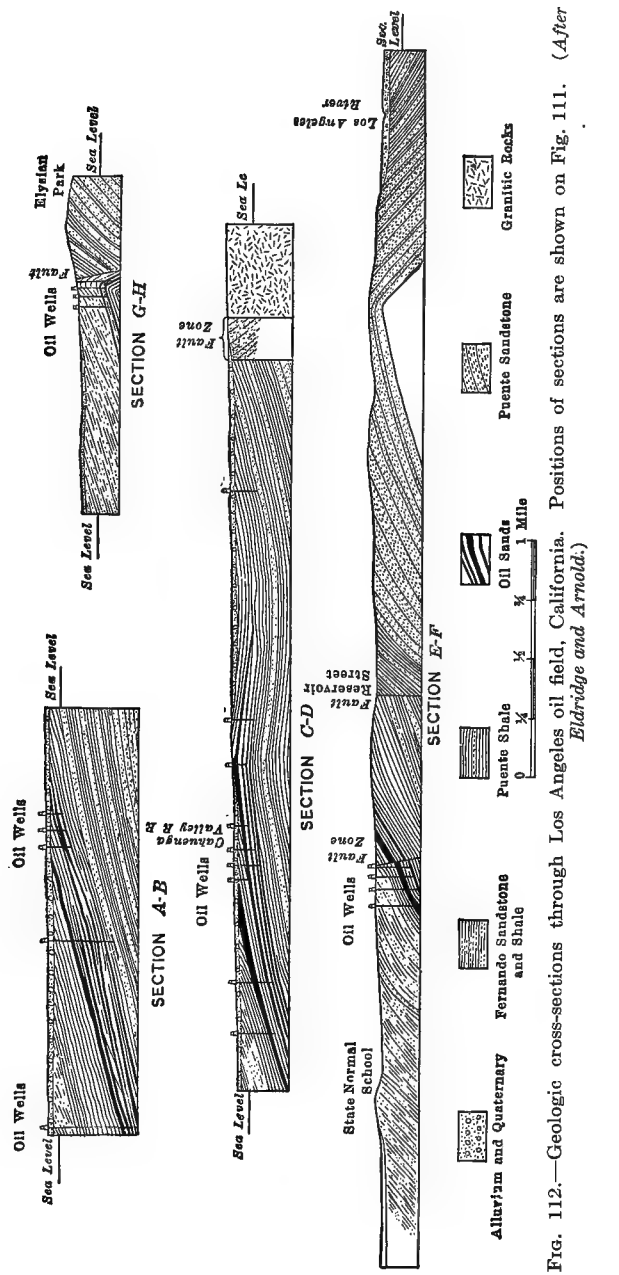


FIG. 112.—Geologic cross-sections through Los Angeles oil field, California. Positions of sections are shown on Fig. 111. (*After Eldridge and Arnold.*)

CANADA

Oil and gas are found at many places[1] in Canda, but thus far oil has been produced on a considerable scale only in Ontario. Gas has been produced in Ontario, Quebec, New Brunswick, and southern Alberta. There is a large area between Hudson Bay and the Canadian Rockies, extending northward to the Arctic region, over which surface indications consisting of oil and gas seeps and tar sands are found. This area has yielded gas at several places and oil near Calgary and Fort Norman. Oil



FIG. 113.—Sketch map of Canada and Newfoundland, showing occurrences of petroleum, natural gas and tar sands. (*After Clapp, Canada Geol. Survey.*)

occurs also in eastern Canada, in Nova Scotia, in New Brunswick, and on Gaspé Peninsula, Quebec. In this region the rocks are consolidated Paleozoic sediments and are rather closely folded and faulted at many places. The prospecting that has been done has resulted in only a small production. Fig. 113 shows occurrences of petroleum and natural gas and of tar sands in Canada.

[1] CLAPP, F. G. and others: Petroleum and Natural Gas Resources of Canada. Canada Dept. Mines. Mines Branch, *Pub.* 291, 2 vols., 1914.

Practically all the petroleum produced in Canada has come from Ontario,[1] from the district lying between Lake Huron and Lake Erie (Fig. 114). Nearly all the Ontario petroleum has come from Lambton County, at the western edge of this district, and from Middlesex County, just east of it. The principal structural features are the domes at Petrolia, at Oil Springs, and in Mosa Township. The oil is derived from the Delaware and the Onondaga limestone of the Devonian, and a little comes from the Trenton limestone.

At Oil Springs, Lambton County, oil issues at the surface along Black Creek just north of the springs. In 1859 attempts were made to utilize oil which exuded from the "gum beds" that formed in the drift. Wells were dug 4 or 5 feet deep, and the

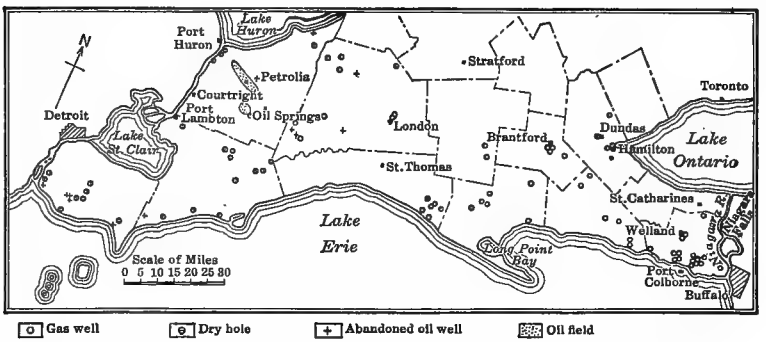


FIG. 114.—Sketch map showing location of oil fields and wells in South Ontario. (*After Clapp.*)

oil would flow into the wells. The principal development, however, began in 1862. At first the arrangements were not adequate to take care of the flow. It is estimated that 5,000,000 barrels of oil were carried off in the streams.

The oil is found in Devonian limestone, which is subdivided into the upper or Delaware limestone and the lower or Onondaga limestone. Oil occurs in both divisions. The largest oil pools occur at the tops of rock domes, only smaller accumulations of oil

[1] BRUMELL, H. P. H.: Natural Gas and Petroleum in Ontario. Can. Geol. Survey *Ann. Rept.*, vol. 5, part Q, pp. 1–94, 1891.

STAUFFER, C. R.: The Devonian of Southwestern Ontario. Can. Geol. Survey *Mem.* 34, pp. 1–341, 1915.

WILLIAMS, M. Y.: Oil Fields of Southwestern Ontario. Can. Dept. Mines Geol. Survey *Summary Rept.* 1918, part E, pp. 30–42, 1919.

being found on terraces. The Petrolia field is a flat-topped, elliptical dome whose longer axis extends northwest.

The Oil Springs field is remarkable not only for its large initial production, but for the size of its present production, considering its small area. The rocks lie in a typical eccentric dome. The oil production is fairly even over the dome except on the northwest side. The oil from the gushing wells of the early days came from a "mud vein" or "crevice" as stated by Williams about 7 to 12 feet from the top of the Delaware limestone. The main production of the present day is from porous limestone 100 to 120 feet below the top of the Delaware.

The following is a typical log:

	Thickness, feet	Depth, feet
Surface	76	76
Petrolia shale, or "upper soap"	113	189
Widder beds, or "middle lime"	17	206
Olentangy shale, or "lower soap"	25	231
Delaware and Onondaga limestone penetrated	163	394
Oil crevice at 240 feet; oil rock between 331 and 351 feet		

A large area in western Canada and the United States, east of and in the Rocky Mountains, exhibits indications of petroleum. The rocks exposed are largely of Cretaceous age. The Cretaceous formations carry oil in Wyoming, Colorado, and Montana and have yielded some oil at Calgary, in Alberta. The Cretaceous[1] yields gas also in Alberta and contains a very extensive body of tar sands on the Athabasca River.

This great area is underlain at many places by the Dakota sandstone.[1] This formation carries artesian water in a large part of the plains region east of the Rocky Mountains and has been encountered in many wells. It is so extensive and its position is known at so many places that it has served as a key rock to plot the structure over a wide area. A paper recently issued[2] shows by contours the structure of a large portion of the area in the United States.

[1] DOWLING, D. B.: Correlation and Geologic Structure of the Alberta Oil Fields. Am. Inst. Min. Eng. *Trans.*, vol. 52, pp. 353–362, 1915.

[2] DARTON, N. H.: The Structure of Parts of the Central Great Plains. U. S. Geol. Survey *Bull.* 691, pp. 1–26, 1919.

In western Canada the Dakota sandstone is extensively developed in Manitoba, Saskatchewan, and Alberta. A little oil has been found in Canada in a sand that has been classed by some as Dakota and by others as the Cloverly, above the Dakota. The Cretaceous, in or near the Dakota, carries gas at Bow Island, at Viking, and at Pelican, Alberta.[1] The tar sands of the Athabasca River are in the Dakota.

MEXICO

The oil fields of Mexico[2] are on the Gulf coast in the States of Vera Cruz, Tamaulipas, and Tabasco. The northern Vera Cruz region (Fig. 115), which includes the ports of Tampico and Tuxpam, supplies almost the total production.

In northern Vera Cruz the coastal plain is about 60 miles wide. The country is comparatively flat and is forested. It is an area of sedimentary rocks intruded by many dikes and plugs of basic igneous rocks. Along the plain the rocks are nearly flat-lying except where disturbed locally by intrusions. To the west, along the east flank of the Sierra Madre Oriental, the sediments are closely folded. The oil is found in rocks of Cretaceous and later age.

The principal oil-bearing rock is the Tamasopa, a series of limestones which make up the core of the Sierra Madre Oriental along the western rim of the coastal plain. The limestones have a slight petroliferous odor. The oil occurs in solution cavities and in other openings in the limestone and is associated with salt water.

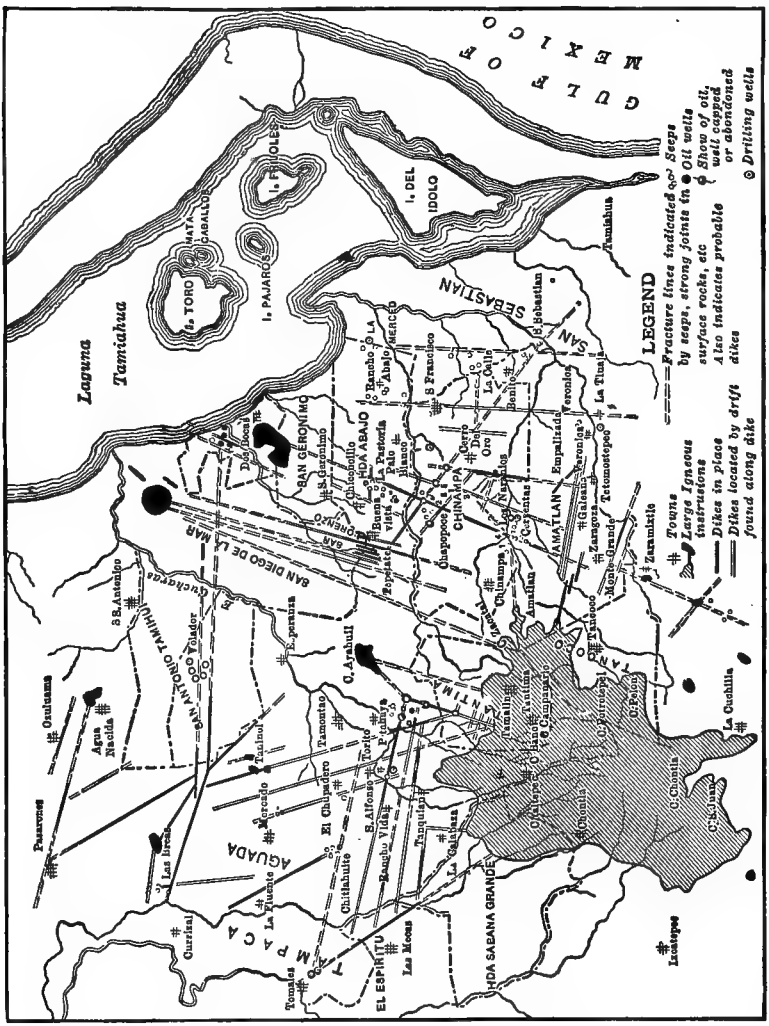
Overlying the Tamosopa limestones in the San Felipe formation, a series of interbedded limestones and shales in which the shale increases toward the top. The San Felipe limestones and shales contain some of the principal deposits of oil in the region. These rocks constitute ideal reservoirs where they are fractured or folded, as near intrusions. The oil occurs to some extent in

[1] HUNTLEY, L. G.: Oil, Gas, and Water Content of Dakota Sand in Canada and United States. Am. Inst. Min. Eng. *Trans.* vol. 52, pp. 329–352, 1915.

[2] GARFIAS, V. R.: The Oil Region of Northeastern Mexico. *Econ. Geol.*, vol. 10, pp. 195–224, 1915; Effect of Igneous Intrusions on the Accumulation of Oil in Northeastern Mexico. *Jour. Geol.*, vol. 20, pp. 666–672, 1912.
HUNTLEY, L. G.: The Mexican Oil Fields. Am. Inst. Min. Eng. *Trans.* vol. 52, pp. 281–321, 1915.

the porous limestones, but more generally, perhaps in interstices in the shales.

Unconformably above the San Felipe beds is a series of uniform


GULF OF MEXICO
Laguna Tamiahua
I. PAJAROS
I. TORO
I. DEL IDOLO
SAN SEBASTIAN
LEGEND
Towns
Large Igneous intrusions
Dikes in place
Dikes located by drift
Fracture lines indicated by seeps, strong joints in surface rocks, etc
Oil wells
Show of oil, well capped or abandoned
Drilling wells
Tuxpam
Tamiahua
Tancochapa
Tamalin
Chinampa
Tamiahua
Tamalin
Tancochapa
Tuxpam
Chinampa
Tamalin
Tancochapa
Tuxpam
Chinampa
Tamalin
Tancochapa
Tuxpam
Chinampa

Dikes, sills, and stocks of basaltic rock intrude the sedimentary beds (Figs. 115 and 116). Most of the surface indications of oil are closely associated with the basalts, and hundreds of them occur throughout the plain. Among the localities where oil seeps are abundant are Panuco, Dos Bocas, Casiano, Tres Hermanos, Ojo de Brea, Chapopotillo, Monte Grande, and many others.

The strata dip eastward from the Sierra Madre Oriental at low angles. This low monoclinal structure has been modified to the south by volcanic intrusions, which, trending in a southeasterly direction, have in this region upturned the monocline slightly to the northwest. Huntley states that all the large wells are located

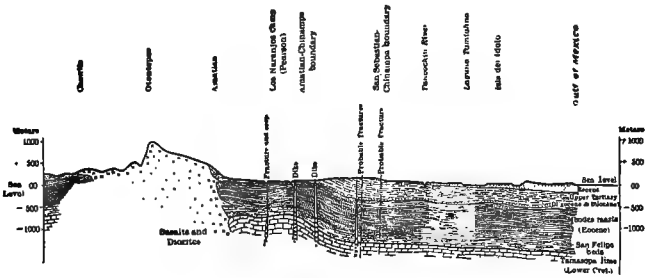


FIG. 116.—Diagrammatic geologic section across southern part of area shown in Fig. 115. (*After Huntley.*)

where there is anticlinal or dome structure and pronounced fracturing of the rock. The fractures are usually accompanied by basaltic intrusions and seeps of asphalt and gas.

SOUTH AMERICA

Oil seeps, and asphalt are found at many places in South America, and oil fields have been developed in Venezuela, Colombia, Peru, and Argentina and on Trinidad Island, off the coast of Venezuela. The oil is found in Cretaceous, Eocene, and Miocene sands and sandstones, and generally on anticlines or domes. The beds in Argentina are almost flat-lying. In Peru some of the wells are on beds that crop out above the wells and the beds are probably sealed up the dip.

Trinidad Island is well known for its great lake where asphalt has been mined for many years, over 2,000,000 tons having been exported. Oil fields have been developed on anticlines within a few miles of the lake. They derive their oil from Miocene strata.

The oil is a fuel oil of low gravity. Recently on an anticline near the center of the island a high-grade light-gravity oil has been found in Cretaceous sands.

In Venezuela oil is found in Cretaceous strata. In Colombia Cretaceous and Tertiary strata yield oil, and prolific fields have recently been developed. The oil-bearing rocks crop out over a large area, much of which is regarded as promising territory.

In Argentina the only producing field is that of Comodoro Rividavia, where oil is found in Cretaceous sandstone. It is a heavy oil and is used for fuel on the Argentine railways. The beds lie almost flat, but the most productive pools are said to be at places where the strata are folded to form domes with very gentle dips.

In northwestern Peru, along the Pacific coast, oil is found in Eocene sands where the strata are thrown into folds. Some of the oil occurs on anticlines and some on monoclines where the beds are sealed up the dip above the well.

EUROPE, ASIA, AND AFRICA

In England oil is found in the Mountain limestone, of lower Carboniferous age, which is covered by Yoredale shales. At Hardstoft, Derbyshire, a faulted dome was drilled in 1919 and oil was found at 3,078 feet. It is a high-grade light-gravity oil rich in paraffin.

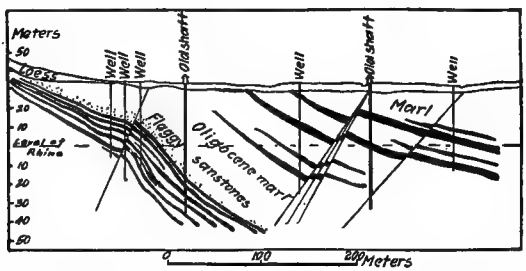


Fig. 117.—Geologic cross-section through the Schwabweiler oil field, Alsace. The dark beds are petroliferous. (*After Audreae.*)

In France oil is found in Alsace, principally in Oligocene sands that are interstratified with marls. The producing beds are lenses on faulted monoclines (Fig. 117).

In Germany oil is found in Prussia north of the Harz Mountains in Upper Jurassic rocks.

In Italy oil has been produced at several places from folded Tertiary strata.

In Galicia, Poland, considerable oil has been produced from Miocene and Eocene sands and some from Upper Cretaceous sand. The prevailing structural features are anticlines, although in places synclines and monoclines are productive (Fig. 118).

In Rumania the Miocene strata yield much oil and the Pliocene a little. The prevailing structural features are domes.

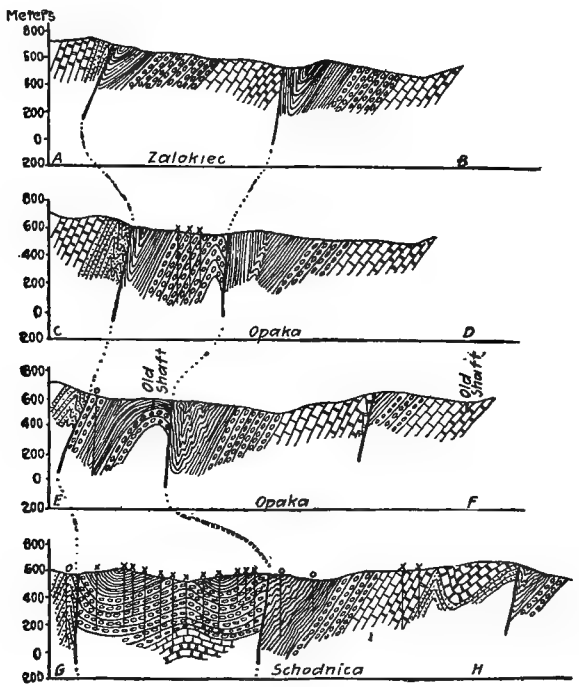


FIG. 118.—Sections showing geology of Zalokiec, Opaka and Schodnica, Galicia. Crosses indicate producing wells, circles barren holes. (*After Zuber.*)

In Russia oil is found in several fields, the principal one of which is Baku, on the Apsheron peninsula, near Caspian Sea. The main oil pools of Baku are the Balakhany-Sabunchy-Romany pool and the Bibi-Eibat pool (Fig. 119).

In the Balakhany-Sabunchy-Romany field the producing strata are Oligocene and Miocene. There are three divisions of oil-bearing sands. The topmost has a thickness of 1,225 feet including the interbedded clays; the thickness of the pay sands

alone is about 600 feet,[1] and individual pay sands range from several feet to 70 feet. This first division is separated from the second by thick water-bearing sands and sandstones. The second oil division has a total thickness of some 600 feet and comprises 280 feet of oil sands. Below these is the lowest and thickest division. This pool covers about 2,500 acres and has yielded over 10 per cent. of the world's total oil production.

The Bibi-Eibat field, which is also one of the most productive in the world, lies 3 miles south of Baku and covers an area of about 1,000 acres. Oil and gas seeps mark the surface, and mud volcanoes are found near by. Structurally the field is an almost symmetrical anticline. The arching beds of the Miocene just reach the surface (Fig. 119) and are flanked by escarpments of

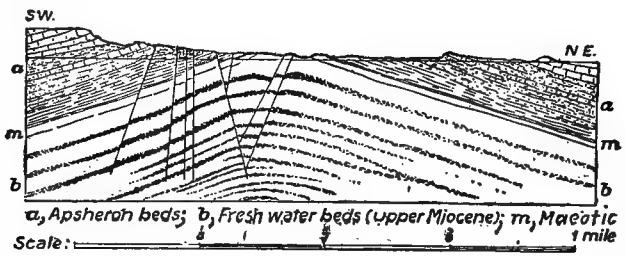


FIG. 119.—Section of the Bibi-Eibat oil field, Baku, Russia. (*After Thompson.*)

the Apsheron limestones. The anticline plunges downward on its landward side and is believed to plunge downward on a fourth side where covered by the sea. The Bibi-Eibat field has produced petroleum since 1880. In 1912 it had yielded 280,500,000 barrels. All the deep waters in the district are brines. Nearly all the Russian oil is heavy fuel oil, but in recent years some lighter oils have been discovered.

In western Persia oil is found on anticlines in sands of Miocene age. It is in the main a heavy fuel oil. The fields have recently been opened and are expected to supply large amounts in the near future.

In Burma oil is found in folded strata of Miocene age, belonging to the Pegu series. The two producing fields, Yenangyaung and Yenangyat-Singu, are located on elongated domes. In Sumatra oil is obtained from Miocene and Pliocene sandstones interbedded with shales and clays. The principal fields are on

[1] Other estimates are considerably lower.

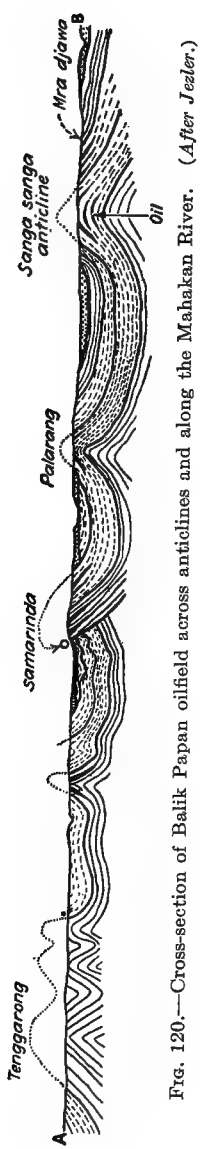


FIG. 120.—Cross-section of Balik Papan oilfield across anticlines and along the Mahakan River. (*After Jezler.*)

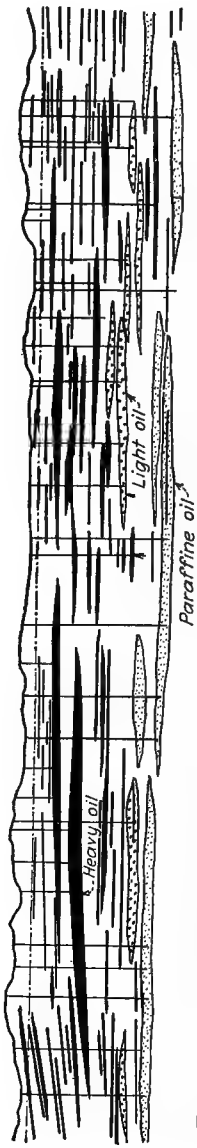


FIG. 121.—Longitudinal profile along the Sanga Sanga anticline showing the position of sands. Black shows positions of sands with heavy oil; dots widely spaced show positions of sands with light oil and dots closely spaced show positions of sands with light paraffine oil. (*After Jezler.*)

anticlines. Some of the oil is heavy fuel oil, but recently a light oil containing considerable gasoline has been found.

In Java oil is found in Miocene beds on anticlines. The oil is of good grade, ranging from 23° to 40° Baumé and contains both asphalt and paraffin. On Madura Island, just east of Java, similar oil fields are found.

In Borneo oil is found in the Tertiary in three separate fields. In the Balik Papan field as shown in Figs. 120, 121, oil is concentrated on folds. Heavy oil is found near the surface and below that lighter oil; at still greater depth a light paraffin oil occurs.

In the Philippine Islands oil seeps from Tertiary rocks are found at many places, but no considerable oil industry is developed.

On Taiwan (Formosa) and in Japan oil is produced from Tertiary rocks.

The principal producing Eurasian oil fields thus form a chain extending with interruptions from Alsace to Japan. Nearly all of the oil comes from Tertiary beds, of which the Miocene are the most prolific. The oil is accumulated in raised structural features except where there has been extensive folding and faulting of unconsolidated rocks near the surface. In general the rocks of this province are not thoroughly consolidated. Although some of the oil is a high-grade light oil, with paraffin base, a larger part of it is low-grade asphaltic oil. The characteristic structural features are domes and anticlines, although oil is found in faulted monoclines in Alsace, in a syncline at Boryslaw, Galicia, at an unconformity at Maikop, Russia, and in fault traps and near salt plugs in Rumania. Deformation affecting the petroliferous strata took place in all these areas in the later part of Tertiary time. There is not a continuous belt of Tertiary strata between the oil-bearing regions named. At some places the Tertiary has been eroded; at other places there were probably islands or larger land masses between the Tertiary seas. In general, however, this region between Alsace, Borneo, and Japan, with an arm extending from Borneo to New Guinea, was a site of deposition in early and middle Tertiary time and of extensive deformation later in the Tertiary.

In Egypt, near the Gulf of Suez, oil is found in Tertiary beds that were deformed in late Tertiary time. This field is closely affiliated with the Eurasian province. Some of the oil of the Suez field, however, is accumulated in Cretaceous sandstone.

OIL SHALES

Certain shales, when heated in a retort, yield oil that resembles petroleum recovered from wells. Such shale is termed oil shale or torbanite. The oil shales are generally dark brown or black and weather gray. Besides organic matter they commonly contain clay, calcite, and some sand. Oil shales burn with a smoky flame. As a rule when broken they give a faint odor of petroleum, but generally they contain little or no oil as such. They do not yield oil to solvents. Their organic material, which on distillation produces petroleum, is called "kerogen."

Oil shales have been exploited in Scotland, in Canada, in New South Wales, and in France. In Scotland they occur a few miles west of Edinburgh in an area 20 miles in diameter. The rocks are of Carboniferous age. The beds are from 1 to 8 feet thick and are mined from shafts. They yield from 15 to 40 gallons of oil and sufficient ammonia to make from 60 to 70 pounds of ammonium sulphate to the ton. The shale that yields most oil is relatively low in ammonia. The industry in Scotland has flourished for many years.[1]

In Canada oil shales are found at many places and have been worked near Albert, New Brunswick. The shales are in the Albert formation, which is of Devonian or lower Carboniferous age.[2] Several beds from 1 to 7 feet thick yielded 27 to 48 gallons of oil and 30 to 110 pounds of ammonium sulphate to the ton.

The shales worked in France are mined from deep shafts and yield 50 gallons of oil to the ton.

In the United States oil shales are not worked on a commercial scale. The largest deposits are in the Uinta Basin, in Utah and Colorado, where a large area is covered by a thick series of shales. The shales are in the Green River formation, a fresh-water deposit of Eocene age. These shales have been mapped and sampled by Winchester,[3] Woodruff and Day,[4] and others.

[1] Stewart, D. R.: The Oil-shale Industry in Scotland. *Econ. Geol.*, vol. 3, pp. 573–598, 1908.

[2] Ells, R. W.: Oil Shale Deposits of Canada. Canada Geol. Survey, No. 1107, pp. 1–75, 1909.

[3] Winchester, D. E.: Oil Shale in Northwestern Colorado and Adjoining Areas. U. S. Geol. Survey *Bull.* 641, pp. 139–198, 1916.

——— Oil Shale of the Uinta Basin, Northeastern Utah. U. S. Geol. Survey *Bull.* 691, pp. 27–55, 1919.

[4] Woodruff, E. G., and Day, D. T.: Oil Shale of Northwestern Colorado and Northeastern Utah. U. S. Geol. Survey *Bull.* 581, pp. 1–21, 1915.

It is said the average yield is between 30 and 40 gallons of oil to the ton.[1] The Green River shales are regarded by many as the greatest potential source of oil in the United States. Alderson,[2] who has recently discussed the problem in considerable detail, is of the opinion that they may now (1921) be distilled profitably. The oil-shale beds are thicker and yield more oil than those of Scotland, but labor would cost more, and the oil and ammonium sulphate would have to be transported farther to a market.

It is believed that the petroleum reserves of the United States will approach exhaustion in two or three decades. Most of the vital industries of the country could probably survive without gasoline or kerosene, but lubricating oil is essential. It is comforting to know that these shales can be made to produce a considerable fraction of lubricating oil of good quality. They will probably find their first and greatest use mainly as a source of such oil.

Oil shales are found also near Elko and Carlin, Nevada, and at many places in the eastern part of the United States. The eastern shales, however, are as a rule of low grade.

SOLID BITUMENS AND BITUMINOUS ROCKS

Asphalt is solid bitumen, formed by the drying of petroleum. Between petroleum and asphalt there are many intermediate substances. They form a series all of which are chemical mixtures, none of them having a definite chemical composition.

The best-known deposit of asphalt is the asphalt lake of Trinidad Island.[3] This deposit occupies about 137 acres and has produced over 2,000,000 tons of asphalt. It is formed by the drying of oil, which rises from beds below the shale. It is hard at the surface and is mined and loaded on a light tramway built out on the lake. The lake is deep, and formerly it was believed that the asphalt was replenished from below, as it was mined, but it has been observed that the level of the lake is lower than when exploitation began. An oil field has been developed in Miocene sedimentary rocks a few miles from the lake.

The asphalt as mined contains much sand and water. On heat-

[1] ALDERSON, V. C.: The Oil-shale Industry, pp. 1–175, New York, 1921.

[2] Some estimates are 50 barrels for certain beds in parts of the field.

[3] WALL, G. P., and SAWKINS, J. G.: Report on the Geology of Trinidad. West Indian Survey, part 1, pp. 1–211, 1860.

ing the bitumen liquefies, the sand sinks to the bottom, and the water is driven off as steam. The asphalt is exported, mainly to the United States and is used for paving streets and in the manufacture of building paper and other building materials.

In Venezuela deposits of bitumen are found at many places. The best known is the Bermudez asphalt lake, so called from the old name of the State in which it lies. This lake is near the coast of the Gulf of Paria, a short distance from Pedernales, in the eastern part of Venezuela not far from the Pitch Lake of Trinidad. The deposit is about 2,500 feet long in a northeasterly direction and from 300 to 600 feet wide. It has yielded large amounts of commercial asphalt which is purer than the Trinidad asphalt and is said to contain only 2.14 per cent. of earthy and vegetable matter. The deposit is not as deep as that of Trinidad.

Mixtures of solid bitumen in which rock predominates are termed asphaltic or bituminous rocks. These are commonly used for paving. In California deposits of bituminous shale, clay and sandstone are found at many places. Bituminous sandstone is quarried at Santa Cruz,[1] 60 miles south of San Francisco. In the main oil fields farther south asphaltic rocks are abundant, especially where the oil-bearing formations crop out. Asphaltic sandstone is found in western Kentucky in the Chester formation. In southern Oklahoma the bituminous rocks include Pennsylvanian and Permian sandstones and Ordovician limestone.

One of the largest deposits of bituminous rocks known is the "tar sand" of Athabasca River, Alberta, Canada. The deposit occupies several thousand square miles and is estimated to be from 15 to 200 feet thick. The sand is of Cretaceous age, but the oil and "tar" which impregnate it are said to have risen through fissures in Devonian limestone, which underlies the deposit.[2] The deposits are not easily accessible and are not worked.

Asphaltic rocks are mined from the Tertiary in Italy and from the Jurassic in France, and at Limmer and elsewhere in Germany.

[1] ELDRIDGE, G. H.: The Asphalt and Bituminous Rock Deposits of the United States. U. S. Geol. Survey *Twenty-second Ann. Rept.*, part 1, pp. 381–407, 1901.

[2] BELL, ROBERT: The Tar Sands of the Athabasca River, Canada. Am. Inst. Min. Eng. *Trans.*, vol. 38, p. 838, 1907.

(CHIEF CHARACTERISTICS OF THE PRINCIPAL VARIETIES OF SOLID BITUMENS)

[After Day]

Name	Common name	Specific gravity	Color	Fusibility
Uintaite	Gilsonite	1.068 to 1.170	Brilliant black powder. Streak lighter brown than albertite.	Fusible in candle flame; burns and acts like sealing wax, leaving sharp impression.
Wurtzilite	Elaterite, Tabbyite, Aeonite, Aegerite	1.0227	Jet-black by reflected light; deep red in thin plates.	Nonfusible in hot water, but softens, toughens, and becomes more elastic. In candle flame melts, burns with bright flame.
Grahamite	Grahamite	1.145	Black, but powder and streak chocolate-brown.	Melts imperfectly with decomposition of surface and the interior may be drawn into threads.
Impsonite[b]	.....	1.175	Jet-black.	Does not soften in boiling water.
Albertite	Albertite	1.08 to 1.11	Black; streak black; powder black to dark brown.	In spirit flame intumesces and emits gas; does not melt; melts in closed tube.
Ozokerite	.....	0.85 to 0.95	Dark.	Fuses at 55° to 70°C.

Bituminous dikes are formed where petroleum enters fissures and becomes hardened before it reaches the surface. The process of hardening is brought about by the loss of more volatile constituents and probably in some places by oxidation. Such dikes during their formation, probably feed gas and oil springs at the surface.

One of the best-known bituminous dikes is the albertite dike in New Brunswick. In this region Paleozoic limestone, shale and sandstone are folded and at some places on edge. The Albert formation consists in places of bituminous shales and sands. It yields as much as 50 gallons of shale oil to the ton and has been distilled on a commercial scale. Surficial indications of oil are widely distributed in this region. The only large albertite vein

(CHIEF CHARACTERISTICS OF THE PRINCIPAL VARIETIES OF SOLID BITUMENS)
[After Day]

Solubility					Composition			
In gasoline (of 76° Baumé)	In ether	In carbon bisulphide	In carbon tetrachloride	In turpentine	Sulphur	Oxygen	Carbon	Hydrogen
					Per cent.	Per cent.	Per cent.	Per cent.
Soluble in petroleum ether.	Slowly; not wholly soluble as powder.	Entirely soluble.	Almost entirely soluble.	Freely soluble in hot turpentine; less soluble in cold turpentine.	1.55	.....	88.79	9.31
Practically insoluble.	About 4 per cent. soluble.	Partly soluble.	Slightly soluble.	Fairly soluble.	5.83	.....	80.00	12.23
Partly soluble.	Partly soluble.	Readily soluble.	.....	Swells and nearly all dissolves.	Tr.	13.46	76.45	7.83
Insoluble	5 per cent. soluble.	Completely soluble.	Partly soluble.	Almost insoluble.	1.47	2.00	86.57	7.26
.....	About 4 per cent. soluble.	Partly soluble.	do	30 per cent. soluble.	Tr.	1.97	86.04	8.96
Soluble.	Soluble.	Soluble.	Soluble.	Soluble.	Tr.	Tr.	85.25	15.09

is that at the Albert mine.[1] This vein was worked to depths of 1,100 feet or more and for half a mile along the strike. At places it is 15 feet wide and sends out apophyses into the country rock. It is nearly straight, stands approximately vertical, and follows the general direction of an anticlinal axis. It has yielded over 200,000 tons of albertite. Manjak is a bituminous material mined in Barbados Island.

[1] ELLS, R. W.: The Bituminous or Oil Shales of New Brunswick and Nova Scotia, part 2, p. 9, Canada Geol. Survey, 1909.

YOUNG, G. A.: Twelfth International Geology Congress Guide Book No. 1, part 2, pp. 366–367, 1913.

CLAPP, F. G., and others: Petroleum and Natural Gas Resources of Canada, part 2, p. 50, Canada Dept. Mines, Mines Branch, 1915.

In Ritchie County, West Virginia, there is a dike of grahamite,[1] nearly a mile long and about 5 feet thick. It stands nearly vertical. The fissure is supposed to have been filled with petroleum largely from the Cairo sand, which lies at a depth of 1,530 feet.[2] The oil filling the fissure, according to White,[3] was gradually converted by oxidation and other processes into grahamite.

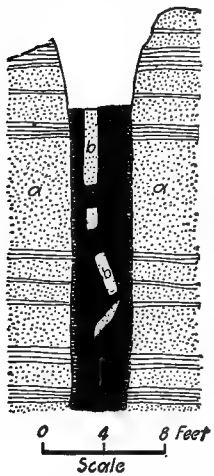


FIG. 122.—Sketch of gilsonite dike at Duchesne mine, Uinta Basin, Utah. (*After Eldridge.*) The gilsonite is black; *a*, sandstone walls of dike; *b*, fragments of sandstone in dike.

Grahamite dikes are found also in south-central Oklahoma.

In the Uinta Basin, Utah, lower Tertiary beds consisting of shales, sandstones, and limestones of the Wasatch and Green River formations dip northward at low angles toward the Uinta Mountains.[4] The section includes several hundred feet of the Green River oil shales, which on heating will yield large amounts of shale oil. In this region dike hydrocarbons are developed in great variety. Asphaltic dikes consisting of gilsonite (Fig. 122), elaterite, tabbyite, albertite, wurtzilite, and nigrite are developed and also dikes of paraffin ozokerite. The asphaltic dikes are found both above and below the oil-shale formation, and the ozokerite dikes below it. The gilsonite dikes are very large and extend for many miles along the strike. Eldridge suggested that the hydrocarbons that filled the dikes were derived from Cretaceous shales and that they came from below under pressure. According to Winchester, however, the Green River oil shale probably supplied the material for the bituminous dikes.

Deposits of solid bitumen in the form of dikes are commonly assocated with gas. In the ozokerite mines of Galicia strong

[1] FONTAINE, W. M.: Notes on the West Virginia Asphaltum Deposit. *Am. Jour. Sci.*, 3d ser., vol. 6, p. 409, 1873.

[2] ELDRIDGE, G. H.: The Asphalts and Bituminous Rock Deposits of the United States. U. S. Geol. Survey, *Twenty-second Ann. Rept.*, part 1, p. 235, 1901.

[3] WHITE, I. C.: Origin of Grahamite. Geol. Soc. America *Bull.*, vol. 10, pp. 277–284, 1899.

[4] WINCHESTER, D. E.: Oil Shales of the Uinta Basin. U. S. Geol. Survey *Bull.* 691, p. 27, 1919.

currents of air are blown into the galleries to remove the gas and prevent injury to the miners. In the Old Black Dragon gilsonite mine, near Black Dragon station, Utah, no explosives are used, and possession of matches in the mines is prohibited under threat of dismissal. Electric lights only are permitted. A disastrous explosion of either gas or fine dust which caused the death of several men is supposed to have resulted from the striking of a match by a miner in defiance of orders. The fire

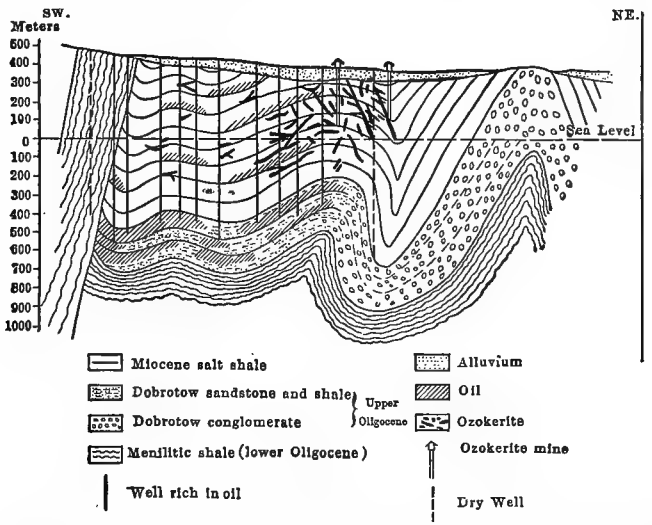


FIG. 123.—Profile through Boryslaw oil field, Galicia, showing Ozokerite dikes near crests of anticlines. Horizontal and vertical scales are the same. (*After Zuber.*)

which ensued melted some of the gilsonite and caused it to run down into the old stopes, so that after the mine was reopened gilsonite was being mined in the same places from which gilsonite had been removed before the explosion.

Ozokerite, or mineral wax, is a native bitumen with a paraffin base. It is essentially paraffin. It is found in Galicia, in England, on Cheleken Island in the Caspian Sea, in the Salt Creek region of Wyoming, and in the Uinta Basin in Utah. It is supposed to be formed by the drying out of paraffin oil. Considering its origin, its occurrence at depths of nearly 2,000 feet at Boryslaw, Galicia, is noteworthy[1] (Fig. 123).

[1] ZUBER, RUDOLPH: Die Geologische Verhältnisse von Boryslaw in Ostgalizien. *Zeitschr. prakt. Geologie.*, pp. 41–48, 1904.

In the Salt Creek region, Wyoming, according to Wegemann,[1] ozokerite is produced by the evaporation of oil that has risen in fissures.

Many natural oils carry paraffin in solution. When these issue in wells, owing to relief of pressure and consequent decrease in temperature, some of them deposit paraffin in the bores. Probably some ozokerite dikes are similarly formed where oil escapes through fissures.

The uses of asphalt for making roads and building materials have been mentioned. Bituminous rocks and the heavy residues obtained from refining oil are also used for making roads. Ozokerite is used for making candles and for many purposes similar to those for which paraffin wax is used. Gilsonite is used extensively for making varnishes and protective paints. Most of that mined in the United States comes from the Old Black Dragon mine, in Utah, on the Uintah Railway.

[1] WEGEMANN, C. H.: The Salt Creek Oil Field, Wyoming. U. S. Geol. Survey *Bull.* 670, p. 36, 1911.

CHAPTER VI

ORIGIN AND CLASSIFICATION OF MINERAL DEPOSITS

DEPOSITS FORMED BY MAGMATIC SEGREGATION

Occurrence.—In igneous rocks, principally in rocks that have crystallized slowly. Some but not all are at the bases or edges of rock units. Some dikes and stocks are all ore or protore.

Composition.—The minerals are the minerals of ingenous rocks.[1] The gangue minerals include quartz, feldspars, pyroxene, olivine, mica, and other rock-making minerals. In general the minerals of the parent country rock and the minerals of the deposit are similar, but the proportions are different. Metals won include iron, nickel, titanium, chromium, platinum, and subordinate copper and gold. Gems include diamond and corundum.

Shape.—Some are irregular in outline, others are rudely ellipsoidal, and still others are tabular.

Size.—Some are small and others are very large. The value of the ore per ton is generally low, and as a rule the deposit must be large to be of commercial value.

Texture.—The minerals are intergrown like the minerals of igneous rocks. Banding, though not uncommon, is not crustified as in veins. Miarolitic cavities are sometimes found in deposits formed by magmatic segregation, but these are not symmetrically lined, as is common in the unfilled portions of veins. The ore is contemporaneous with the parent country rock and grades into it, although in some deposits the gradational zones are narrow. Contacts with rocks that are not contemporaneous are not gradational. The rocks are not hydrothermally altered at the time of deposition of the ore. Idiomorphic rock-making crystals may be inclosed in the ore minerals. Fragments of intruded rock may be included in the ore.

Magnetic differentiation is the process by which a magma or molten rock stuff of supposed uniform composition splits up into bodies of different composition.[2]

Under some conditions in a magma the heavy material settles to the bottom and the lighter material rises to the top, perhaps

[1] An outline of the classification of mineral deposits is stated on pp. 5 to 8. In this chapter the characteristics of each class are set forth.

[2] Vogt, J. H. L.: Bildung von Erzlagerstätten durch Differentiationsprocesse in basischen Eruptivemagmata. *Zeitscher. prakt. Geologie*, vol. 1, pp. 4–11, 125–143, 257–284, 1893.

after the manner of separation of metals from slag in a blast furnace. Segregation may thus take place before crystallization begins. Magmas are solutions and obey the laws of solutions. Thus the minerals that solidify or separate out from a cooling magma do so in the order of their saturation points under the conditions that prevail. As a general rule the more basic materials, such as iron, magnesium, and titanium minerals, will crystallize first. These in the main are the oxides and sulphides. As crystallization goes on the liquid portion generally becomes more and more acidic or siliceous, although some silica also may crystallize out early in the process. If viscosity is not too high, the heavy minerals fall. Later, if pressure is relieved by extravasation of the upper lighter molten liquid, the heavier material remaining at the bottom, owing to relief of pressure, may be remelted.[1]

Becker[2] has shown also that fractional crystallization on cooling, in a dike or laccolith, may cause differentiation. Along the cooler walls the less soluble material will crystallize first, and convection currents will tend to carry the more soluble material into the still liquid portion of the mass, where it will later solidify. Thus the less soluble material will predominate on the outer walls.

In some igneous rocks that carry diamonds and corundum these minerals are broken, showing that they had formed before the magma came to rest. They were probably formed at a depth greater than that at which solidification of the rock took place.

Magmatic differentiation is not fully understood, yet there is much evidence that it has operated, for commonly an igneous rock grades almost imperceptibly into another igneous rock of different composition, although the two have formed from the same molten body.[3]

One other aspect of the subject of ores associated with igneous rocks should be mentioned. Practically all investigators agree that the magmas, or the igneous rocks, are the sources of all mineral matter. The study of the genesis of mineral deposits

[1] Schweig, Martin: Differentiation der Magma. *Neues Jahrb.*, Beilage Band 17, p. 516, 1903.

Iddings, J. P.: The Origin of Igneous Rocks. Phil. Soc. Washington *Bull.* 12, pp. 89–130, 1892.

[2] Becker, G. F.: Some Queries on Rock Differentiation. *Am. Jour. Sci.*, 4th ser., vol. 3, pp. 21, 260, 1897.

[3] One of the clearest discussions of differentiation of magmas is that by L. V. Pirsson in U. S. Geol. Survey *Bull.* 237, pp. 181–190, 1905.

is a study of the processes of their concentration from igneous rocks (Fig. 124). Processes operating in the magma may cause differentiation and segregation of workable bodies. Low-grade materials of magmatic origin may on weathering become rich residual masses, or they may weather and be subsequently reconcentrated by mechanical or chemical processes, forming sedimentary beds. Meteoric waters may dissolve the valuable constituents from the solid igneous rock and concentrate them by precipitation in openings. But magmas carry water and other fluids that solidify at low temperatures, and during crystallization these fluids may escape. Coursing through fissures and reacting with rocks, they precipitate metals and other elements with which they are charged, and in the higher regions they mingle with

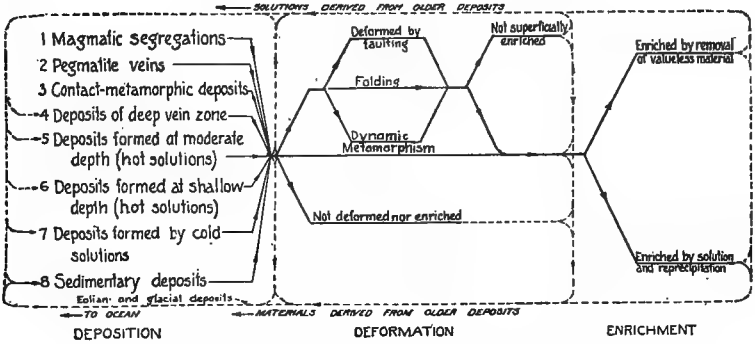


FIG. 124.—Diagram illustrating mode of deposition, deformation, superficial alteration, and enrichment of ore deposits and protores. Diagram shows also how deposits may be broken down mechanically or dissolved and their products may enter new deposits. It is helpful to trace out on the diagram the genesis of several typical deposits.

ground water, which generally causes further precipitation of mineral matter. Ultimately they may escape as hot springs.[1]

Magmatic segregation does not occur ordinarily in surface lavas. These bodies cool quickly, and appreciable segregation rarely takes place in them. Owing to the relief of pressure when they are poured out, steam and other gases which aid diffusion readily escape. At a few places gems and metals are found in surface lavas, such are probably due to magmatic segregation

[1] KEMP, J. F.: The Role of the Igneous Rocks in the Formation of Veins. In POSEPNY, F.: The Genesis of Ore Deposits, pp. 681–809, 1902.

before eruption, but they are of relatively small value. The deep-seated rocks, especially the basic rocks, such as norite, gabbro, and peridotite appear to be especially favorable to magmatic segregation. The more acidic rocks, on the other hand, are more fruitful as sources of epigenetic ores. Lithium, tungsten, tin, and some other elements are characteristically associated with the acidic magmas; nickel, platinum, and chromium are associated with basic or ferromagnesian magmas. Some iron deposits appear to have segregated from moderately acidic rocks.

Gravity and fractional crystallization tend to segregate portions of the magmas at the bottom or on the sides of rock units. Among the deposits found in such positions a conspicuous ex-

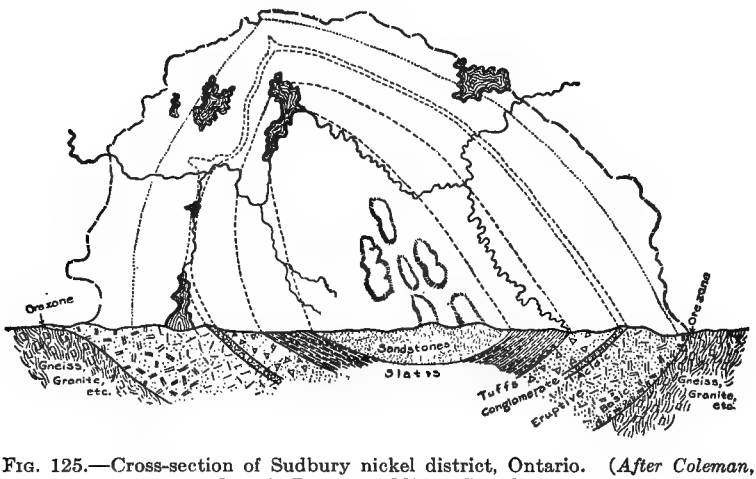


FIG. 125.—Cross-section of Sudbury nickel district, Ontario. (*After Coleman, Ontario Bureau of Mines, Canada.*)

ample is that of the nickel ores of the Sudbury nickeliferous eruptive mass (see Fig. 125). On the other hand, many deposits formed by magmatic segregation are entirely surrounded by the parent rock. Some dikes and stocks are essentially all ore or protore. Such bodies are assumed to be the products of magmas as differentiated before extravasation.

As deposits due to magmatic segregation are igneous rocks, their minerals are exclusively the igneous rock-making minerals and their alteration products. Some of the more important minerals are named below.

allanite	diopside	molybdenite	quartz
amphiboles	feldspars	monazite	rutile
apatite	fluorite	muscovite	sapphire
augite	garnet	nepheline	silver
biotite	gold	olivine	specularite
cassiterite	graphite	pentlandite	spinel
chalcopyrite	hematite	picotite	titanite
chromite	ilmenite	platinum	topaz
corundum	iron	pyrite	tourmaline
diallage	magnetite	pyroxenes	xenotime
diamond	melilite	pyrrhotite	zircon

Some valuable minerals, like diamonds, sapphires, and rubies, are sparingly disseminated in igneous rocks. In some deposits the rock mass exposed may be essentially homogeneous, and any magmatic differentiation must have taken place before the body now exposed came to rest. The entire mass is then the mineral deposit. Such masses obviously may be tabular dikes (like the sapphire deposits at Yogo, Mont.) or irregular stocks (like the Kimberly diamond deposit), or they may be irregularly shaped like any irregular intrusive igneous body. Some deposits of titaniferous magnetite are simply igneous dikes. A deposit that forms only part of the parent rock mass is generally irregular, but some of these also are broadly tabular. In general, however, deposits segregated in the parent magma approach the tabular form less closely than fissure veins or sedimentary beds.

In size the deposits due to magmatic segregation are exceedingly diverse. Among the large ore bodies formed by this process are certain deposits of magnetic iron ores that aggregate millions of tons and the enormous deposits of nickel-copper ores in Sudbury, Ontario. On the other hand, small segregated deposits of chalcopyrite, galena, and chromite may be too small to be of value.

The constituent minerals of these deposits are generally mutually interlocked, like the minerals of granular igneous rocks. In some deposits magnetite, pyrite, olivine, and certain other minerals have crystallized out before the more siliceous minerals, such as feldspar and quartz. If the deposit has been formed by the separation of falling metalliferous crystals, the ore minerals, which are the heavier constituents, should be among the first minerals that were formed in the overlying country rock, for they could not have fallen through a mass already solidified. The original rock minerals are not hydrothermally altered in these deposits, as they are in the wall rock along veins deposited from

thermal waters. As the deposits formed by magmatic segregation are not metasomatic, pseudomorphous replacements are



FIG. 126.—Iron ore formed by magmatic segregation, from Iron Lake, Minnesota. Dark is intergrowth of magnetite and ilmenite; light is feldspar. (*After Singewald.*)

unknown in the original ore. In many of the ores the ore minerals have crystallized after the gangue minerals[1] (Fig. 126).

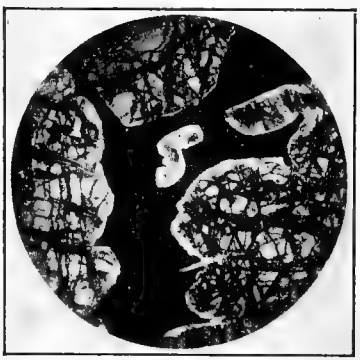


FIG. 127.—Pyrrhotite (black) with olivine (light). The dark bands traversing the olivine are lines of magnetite inclusions Enlarged about 15 diameters. (*After Bastin.*)

If the sulphide ores inclose well-shaped (idiomorphic) crystals of feldspar (as shown in Figs. 126, 127), there is a very strong probability that the deposit is due to magmatic segregation.

[1] TOLMAN, C. F., and ROGERS, A. F.: Stanford University, *Pub. Univ.* series, pp. 1–76, 1916.

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ROBERTS, HUGH M., and LONGYEAR, ROBERT DAVIS: Genesis of the Sudbury Nickel-Copper Ores as Indicated by Recent Explorations. Am. Inst. Min. Eng. *Trans.*, vol. 59, pp. 27–56, 11 Figs. Discussion by G. F. Kunz, F. F. Grout, W. G. Miller, A. M. Bateman.

TOLMAN, C. F., and ROGERS, A. F.: A Study of Magmatic Sulphide Ores. Stanford University *Pub. Univ.* Series, pp. 1–76, 1916.

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PEGMATITES

Occurrence.—In or near deep-seated igneous rocks; many are near the outer margins of intrusives. Where pegmatites intrude sedimentary rocks or schists, they generally follow bedding planes or the planes of schistosity, but locally they cut across such planes.

Composition.—The minerals are essentially the minerals found in igneous rocks, but the range in composition of pegmatites is less than that of the igneous rocks. Feldspar, quartz, and mica are very common constituents. Many rare minerals and gem minerals are found in pegmatites. They are the sources of lithium minerals, monazite, and xenotime. Metals include tin, tungsten, bismuth, yttrium, thorium, tantalum, iron and others.

Shape.—Many pegmatites have very irregular outlines, especially those which lie within the parent igneous rock. A large number of pegmatites are rudely tabular. Pipe-like and dendritic bodies are represented.

Size.—Pegmatites range in size from minute bodies to masses that extend over many acres. Where the material has been injected in highly foliated schist, the individual pegmatite sheets may be paper thin. Metalliferous concentrations in pegmatites are generally small.

Texture.—The crystals are usually large and commonly are intergrown as in igneous rocks. Some pegmatites grade into the containing parent rock.

Miarolitic cavities are common. Banded or comb structure and openings with crustified bands are developed in some pegmatites, but such features are much less common than in normal ore veins. Fluid inclusions are locally abundant.

Magmas generally contain gases and other constituents that remain fluid at comparatively low temperatures. Some of these may solidify during the late stages of cooling and segregate in veins or irregular masses called pegmatites. Pegmatites are in a strict sense formed by magmatic segregation, but pegmatites generally contain crystals that are larger than those of the parent rock. Certain materials that were found by experiments to facilitate crystallization were termed "mineralizers" by Daubrée. These include water, compounds of fluorine, beryllium, boron, chlorine, tungsten, and others. Many pegmatites are known to contain small amounts of these substances, which are believed to have aided in keeping the material fluid until a late stage.

When certain mixtures cool the last materials to solidify have a definite composition and a melting point that is lower than that of any other mixture of the material. The mixtures with a lower melting point than any other mixtures are called "eutectic." Likewise in pegmatites there is a tendency toward uniformity in composition, as was shown by Vogt and by Teall. There are certain variations, however, due probably to the complexity of the mixtures or chemical systems.

Many pegmatites are composed of feldspar and quartz. Others contain mica also, and still others contain these minerals with small amounts of tourmaline (contains boron), beryl (contains beryllium), and many gems, such as topaz, ruby, and sapphire. The gems are commonly found in small pockets in the pegmatite (Fig. 128).

The pegmatites are not very prolific of the metals, but they yield a little tin, tungsten, molybdenum, thorium, lithium, and yttrium, and some of them contain gold. They are of great scientific interest but of comparatively little economic value.

Pegmatites are associated with deep-seated igneous rocks, generally with the siliceous rocks, less commonly also with basic rocks. Rhyolites, basalts, and other surface lavas and intrusive rocks formed near the surface are not accompanied by pegmatites; consequently it is assumed that great pressure is necessary for their genesis. As the deep-seated rocks cool, the end products of crystallization may segregate, and the segregated materials

include the more soluble compounds of the magma. Certain investigators have applied to such end products of crystallization the term "granite juice"—a term that implies mobility, which is a striking characteristic of the pegmatitic solutions. The end products are more mobile than the parent magma because of their excess of gases, and if fissures are formed in the solidified portion of the magma or in the country rock near by, the pegmatitic material may be injected into them. Pegmatites

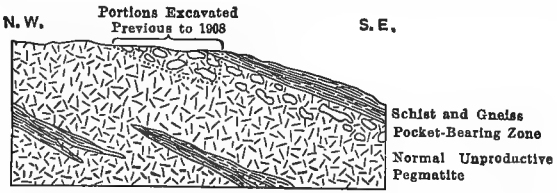


FIG. 128.—Sketch of pegmatite with zone of tourmaline pockets near the top. Mount Mica, near Paris, Maine. (*After Bastin, U. S. Geol. Survey.*)

may therefore follow cracks, planes of schistosity, or any openings or planes of weakness that were accessible. The pegmatitic solution may even force itself into the surrounding rock, making the opening as well as filling it. To such processes are doubtless due "leaf injections," in which paper-thin sheets of pegmatite alternate with thin sheets of schists.

The crystals of pegmatites are generally large. A spodumene crystal in the southern Black Hills is 50 feet long. In many pegmatites the feldspar crystals are an inch long or more. The gases that the magmas carry, or "mineralizers," are believed to have aided in the formation of the large crystals. Some of the minerals found in pegmatites are listed below.

albite
allanite
amphiboles
anorthite
apatite
arsenopyrite
beryl
bismuth
bismuthinite
biotite
bornite
calcite
cassiterite
chalcopyrite
corundum
diamond
diopside
emerald
fluorite
galena
garnet
gold
graphite
hematite
ilmenite
kyanite
lepidolite
magnetite
microcline
molybdenite
monazite
muscovite
orthoclase
pyrite
pyroxenes
pyrrhotite
quartz
rhodochrosite
rhodonite
ruby
rutile
sapphire
scheelite
specularite
spinel
spodumene
tantalite
titanite
topaz
tourmaline
wolframite
xenotime
zinc blende

Many pegmatites are very irregular in shape, especially those remaining in the parent rock, and of these some have weird shapes that are very puzzling. The dendritic mass or branching pipe figured by Butler (see Fig. 129) is believed to have been formed by movement of the pegmatitic solution in a cooling but still viscous mass of the parent magma. Some pegmatites are sheet-like, and others are long in one and short in two dimensions. The thin, rudely tabular mass is perhaps the most common form. In some pegmatites the minerals are arranged in bands (Fig. 130).

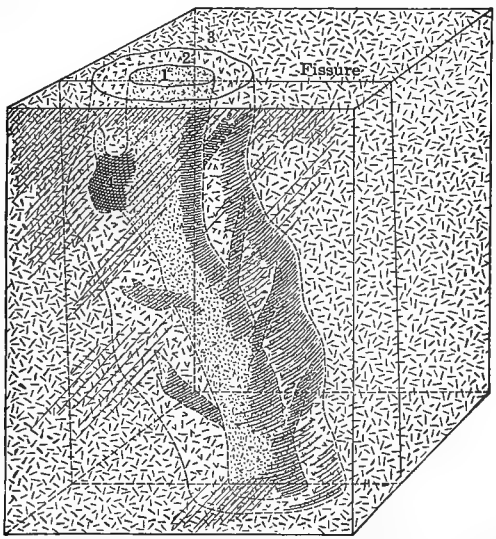


FIG. 129.—Generalized stereogram showing the relation of pegmatitic quartz and altered and mineralized quartz monzonite in the O. K. mine, San Francisco region, Utah. 1, Pipe of quartz; 2, altered monzonite; 3, monzonite; 4, high-grade ore consisting of chalcopyrite, molybdenite and other minerals. (*After Butler, U. S. Geol. Survey.*)

From their associations it is believed that pegmatites are normally formed at high temperatures. This inference is supported by the work of Wright and Larsen,[1] who utilized the discovery of Mügge, namely, that when quartz is heated it suffers at 575°C. an enantiotropic change to a second phase, called β-quartz by Mügge, and that above 800° it is no longer stable at ordinary pressures but passes into tridymite. The change from the stable form, called α-quartz by Mügge to β-quartz is attended

[1] WRIGHT, F. E., and LARSEN, E. S.: Quartz as a Geologic Thermometer. *Am. Jour. Sci.*, 4th ser., vol. 27, pp. 421–447, 1909.

by an abrupt change in the birefringence, circular polarization, and expansion coefficient at that temperature. Cold quartz that was formed above 575° will show certain changes, such as

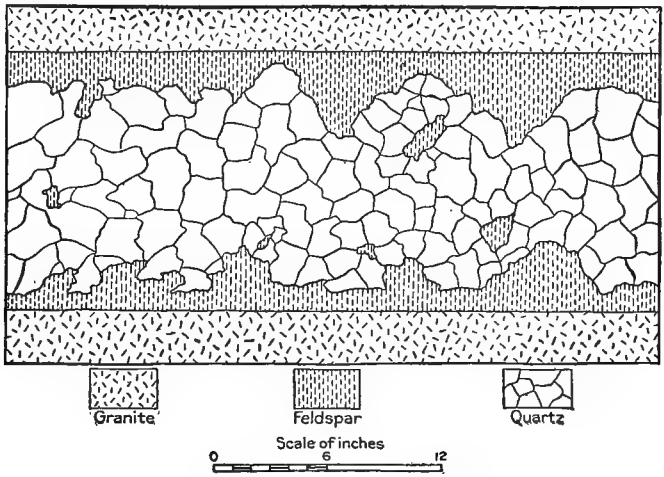


FIG. 130.—Sketch of layered pegmatite dike. (*After Graton, U. S. Geol. Survey.*)

fracturing and irregular twining. Examinations by Wright and Larsen showed that many pegmatites have formed below 575° and some above that temperature.

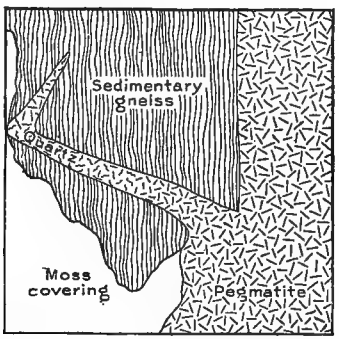


FIG. 131.—Quartz offshoot from pegmatite, Paris, Maine. (*After Bastin, U. S. Geol. Survey.*)

Although few pegmatites grade directly into ore veins, there are well-established examples of pegmatites that grade into quartz veins, such as those at Paris, Maine, described by E. S. Bastin (Fig. 131).

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CONTACT-METAMORPHIC DEPOSITS

Occurrence.—(1) In soluble or replaceable rocks—limestones or calcareous shales,—more rarely in quartzites and igneous rocks

2. Near intruding igneous rocks of intermediate or acidic composition, such as diorites, granodiorites, monzonites, granites, or their porphyries; more rarely at contacts of basic rocks, such as gabbros and diabases. Not genetically related to surface lavas or glassy rocks.

3. Most of them touch or lie within a few rods of the outcrops of igneous rocks, but they may be as much as 100 rods away, or rarely farther. Some form broken or disconnected belts around the igneous masses. The ores are generally segregated in irregular bunches or large masses in the contact-metamorphic zones. In some examples the intruding rock is itself altered.

Composition.—The minerals are characteristic. The ore is commonly a mixture of silicates intergrown with oxides and sulphides of metals. The non-metallic minerals include graphite and corundum. The metals include copper, iron, zinc, tungsten; more rarely gold, silver and lead.

Shape.—Generally irregular in detail; deposits nearly equidimensional are common; some are rudely tabular; many show gradational boundaries with rocks intruded.

Size.—From bodies yielding a few tons to large masses.

Texture.—The ore minerals are commonly intergrown with the contact-metamorphic silicates. Where shale or other banded rocks are replaced the ore may be banded, but there is no crustified banding. Vugs are rare, if not lacking.

Intruding igneous rocks give off solutions that invade and change the rocks that are intruded (Fig. 132). The solutions commonly carry valuable metals, which are deposited near the contact. Deposits of this character are due to replacement of the country rock, and because they were formed at high temperature many of them contain certain minerals that are characteristic of high-temperature deposits. Garnet, wollastonite, actinolite, and micas, as shown by Lindgren,[1] are intergrown with quartz calcite, and sulphides and oxides of the metals. The ores of

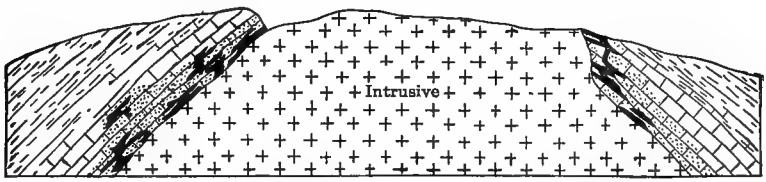


FIG. 132.—Diagram showing relations of contact metamorphic-deposits (black) to contact metamorphic zone (stippled) and to intrusive mass.

metals are generally irregular in their distribution; they occur in pockets, in layers, and in irregular masses (Fig. 133). As a rule the contact is not continuously metallized, but the deposits are found here and there in the contact zone, many of them lying several rods from the contact. They are rarely related to easily recognized openings. At many places the solutions seem to have soaked into the rock invaded, following presumably the cleavage planes of minerals and intergranular spaces.

Some of the deposits consist of only one or two minerals; other deposits carry many of them. The contact zone is made up of materials that were present in the rock invaded, plus the materials that were introduced, minus the material of the original rock that was carried away by solutions. In many of the deposits the minerals of the ore of the sulphide and heavy silicate type are intimately interlocked and were formed approximately at the same time. The silicates, such as garnet, vesuvianite, tremolite, diopside, and the micas, and the oxides, magnetite and hematite, are commonly intergrown with pyrite, chalcopyrite, zinc blende,

[1] LINDGREN, WALDEMAR: The Character and Genesis of Certain Contact Deposits. Am. Inst. Min. Eng. *Trans.*, vol. 31, pp. 226–244, 1901.

and other sulphides. Residual calcite is almost invariably present. The greasy appearance of the massive garnet and vesuvianite where freshly broken, the feathery texture of ore composed in part of actinolite or tremolite, and the greenish, flaky appearance of ore in which the micas and chlorite predominate are more or less characteristic of the sulphide-silicate rock.

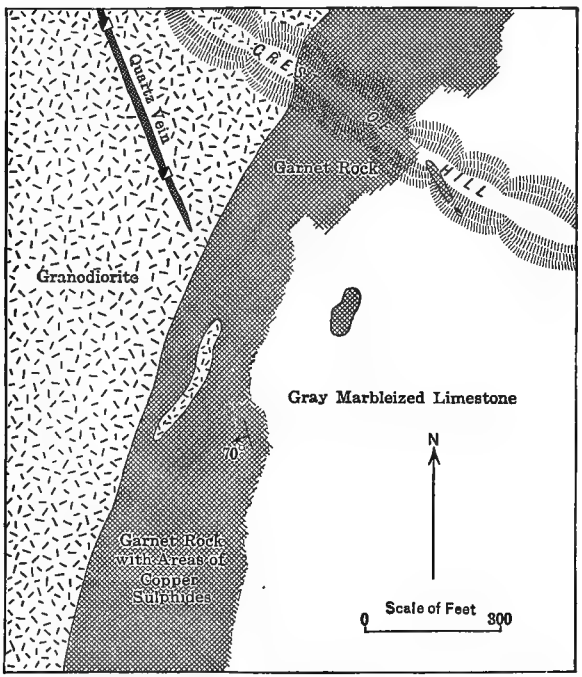


FIG. 133.—Sketch showing the relation of the zone of contact metamorphism to granodiorite and limestone. Bullion district, Nevada.

In some contact metamorphic ores the sulphides were formed after the silicates. Contact metamorphism is doubtless a slow process. At early stages the deposition of silicates probably predominates; later the sulphides are deposited in larger proportions. Thus at some places the silicates may be cracked and filled by sulphides. In the Seven Devils region, Idaho, according to Livingston and Laney,[1] the sulphides in the contact zone locally replace the heavy silicates.

[1] LIVINGSTON, D. C., and LANEY, F. B.: Copper Deposits of the Seven Devils and Adjacent Districts, Idaho. Idaho Bureau of Mines and Geol. *Bull.* 1, p. 62, 1920.

The ore in the contact silicate zone is commonly erratic. In many contact metamorphic zones, however, as shown by Umpleby,[1] the sulphides are found on the limestone side of the garnet zone. This relation is shown by Fig. 134, which is a section from the Seven Devils region, Idaho. According to Umpleby the solutions from the magma probably changed their chemical character during contact metamorphism, so that silicates are formed mainly at an early stage of contact metamorphism, when the sulphides are deposited in small amount At a later stage the sulphides were deposited probably with smaller amounts of silicates. This conclusion is in accord also with the observations of Umpleby[2] in the Mackay district, Idaho.

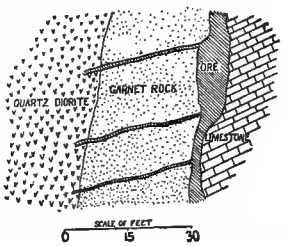


FIG. 134. — Section showing ore developed on the limestone side of the contact metamorphic garnet zone in Queen No. 1 Mine, Seven Devils, Idaho. (*After Umpleby, U. S. Geol. Survey.*)

At a few places contact-metamorphic deposits are found where no igneous rocks are exposed near them. At such places the igneous rocks presumably lie at depths not yet explored.

The following minerals are among those that have been identified in contact-metamorphic zones:

actinolite	calcite	graphite	quartz
albite	cassiterite	hematite	rutile
allanite	chalcopyrite	humites	scapolite
amphiboles	chlorite	ilmenite	scheelite
andalusite	chromite	ilvaite	sericite
andradite	corundum	jadeite	specularite
ankerite	cordierite	magnetite	spinel
anorthite	diopside	microcline	titanite
anthophyllite	dolomite	molybdenite	topaz
apatite	emerald	muscovite	tourmaline
arsenopyrite	emery	olivine	tremolite
augite	epidote	orthoclase	vesuvianite
axinite	fluorite	picotite	wollastonite
beryl	franklinite	pyrite	zinc blende
bismuthinite	galena	pyroxenes	zincite
biotite	garnet	pyrrhotite	zoisite
bornite	gold		

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Mineralogically contact-metamorphic deposits are closely related to veins of the deep zone. In many regions that contain contact-metamorphic deposits fissure veins (Fig. 135) and disseminated deposits also are developed.

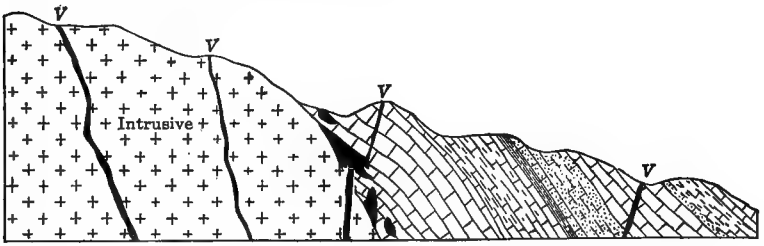


FIG. 135.—Section showing sedimentary rocks intruded by igneous rock, with contact-metamorphic deposits (irregular black areas) and veins.

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DEPOSITS OF THE DEEP VEIN ZONE

Occurrence.—Found generally in or near intrusive bodies of deep-seated igneous rocks that have been deeply eroded. Not genetically related to surface lavas and intrusives formed near the surface. Rarely found in the younger rocks.

Composition.—The minerals are approximately the same as those formed in contact-metamorphic deposits, but quartz is as a rule more abundant. Gangue minerals include garnet, amphiboles, pyroxenes, and micas. Some veins are worked for graphite. Gangue minerals containing elements of the "agents of mineralization" are commonly present. The simple sulphides of the metals are frequently associated with metallic oxides. Gold, tin, iron, zinc and copper are the most important metals in these deposits. Tungsten and molybdenum also are present in a few of the veins of the deep zone.

Shape.—Some of the deposits are tabular; others are of irregular shape. Stockworks and stringer leads are developed. The large, regular tabular bodies, which predominate in the group of deposits formed nearer the surface, are represented but are proportionately less numerous in the deep-vein zone. Sheeted zones, bedding-plane deposits, saddles, and anticlinal deposits are developed.

Size.—Many of the individual deposits are small; some are large.

Texture.—The lodes are commonly banded. Vugs are locally present. Fluid inclusions are common. Where banded rocks are replaced by ore, the ore may retain the banding. Comb quartz and symmetrical crustification are not unknown, but these features are not so conspicuously developed as in deposits that were formed nearer the surface. Disseminated ore may be formed.

Deposits of the deep vein zone are formed at high temperature and under great pressure, in and along fissures or other openings. Although this group is represented by numerous valuable deposits in the United States, it is as a whole less important economically than the group of deposits formed at moderate depth and lower temperature. Ore veins are more commonly formed relatively near the surface, where rocks are more easily fractured and where ascending solutions are more readily cooled in part by mingling with cold surface waters. The Cornwall tin and copper deposits, which are among the most notable examples of the

deep veins, have been enormously productive. In the United States the gold veins of the Appalachian region (Fig. 136) and the Homestake ore bodies of the Black Hills are the best-known representatives.

Deposits of the deep vein zone form a connecting link between pegmatite veins and contact-metamorphic deposits, on the one hand, and veins formed at intermediate depths, on the other. Because they were formed at high temperature and high pres-

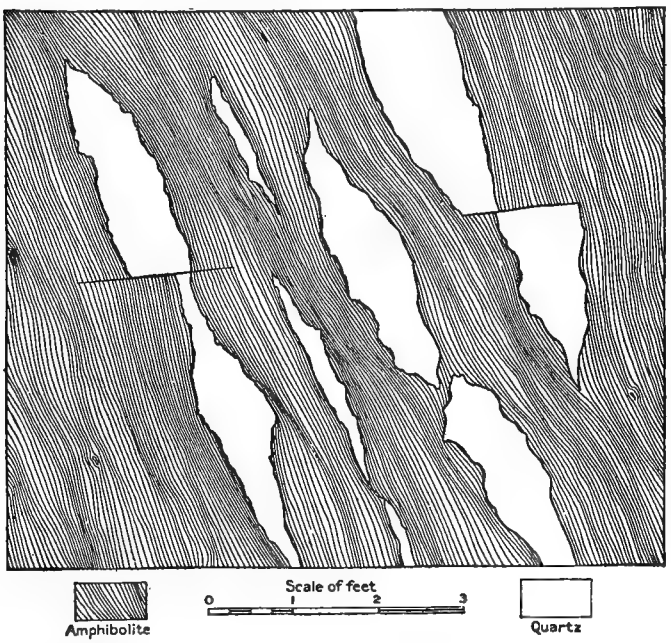


FIG. 136.—Vertical section in Schlegelmilch mine, York County, South Carolina, showing lenticular bodies of quartz in amphibolite schist. (*After Graton, U. S. Geol. Survey.*)

sure, they contain many of the minerals that are found in contact-metamorphic deposits. They differ from contact-metamorphic deposits, however, in that they are generally related to clearly defined fissures, and a large number of them are found farther away from contacts of intruding and intruded rocks. Although as a rule, they are irregular in form, they are more generally tabular than contact-metamorphic deposits.

The principal minerals are listed below.

amphiboles	cryolite	ilmenite	siderite
anhydrite	epidote	magnetite	silver
apatite	fluorite	molybdenite	specularite
arsenopyrite	feldspar	muscovite	topaz
bismuthinite	galena	pyrite	tourmaline
biotite	garnet	pyrrhotite	willemite
bornite	gold	quartz	wolframite
calcite	graphite	rutile	zinc blende
cassiterite	hematite	scheelite	zincite
chalcopyrite	hornblende	sericite	zoisite
chlorite			

The minerals are commonly intergrown. Like those of contact-metamorphic deposits they have been formed largely by replacement, but the replacing solutions generally deposit the metals in or not far from easily recognized fissures.

Quartz is abundant in many deposits of the deep zones. Much of it contains fluid inclusions with gas bubbles and associated solids. Quartz crystals may project into open spaces or vugs, but the comb structure in which long parallel crystals of quartz alternate with layers of sulphides and other minerals, characteristically developed in open spaces near the surface, is less common in the deep vein zone. In some, however, quartz is banded with other minerals. Garnet is not everywhere developed, but in some veins it is abundant.

The depth at which these deposits have been formed is not everywhere easily calculated. Some were formed within a mile of the surface; others probably at depths of 2 or 3 miles.

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DEPOSITS FORMED AT MODERATE DEPTHS BY HOT SOLUTIONS

Occurrence.—In or near igneous rocks; most of them are near intrusive rocks.

Composition.—Contain a great variety of minerals. Complex sulphosalts of antimony and arsenic are common; metals include copper, silver, gold, zinc, arsenic, antimony, subordinately nickel, cobalt, bismuth, manganese, tungsten, etc. Pyrite and quartz are common.

Shape.—The deposits are in the main tabular bodies or combinations of tabular bodies. Sheeted zones, fracture zones, stockworks, and pipes are developed. In limestone many of the ore bodies are chambers. "Saddle reefs" and bedding-plane deposits are developed.

Size.—Some of the ore bodies are large; many are small.

Texture.—The veins that fill fissures are generally banded, and in them comb structure and drusy cavities with symmetrical crustified banding are common. The ore which replaces the wall rocks does not form crusts but may be banded. Pseudomorphous replacement of shales, schists, or other banded rocks will also give banded ores which are not symmetrically crustified. Valuable bodies of disseminated ores belong to this group; in these the rock is cut by many small fractures partly filled with ore minerals, and the rock between the fractures is impregnated or peppered with little dots of ore.

Many valuable deposits have been formed at moderate or intermediate depth by precipitation from hot solutions. These deposits are extensively developed in the western part of the United States. They yield most of the copper, zinc, and lead and much of the gold and silver mined in Western States.

The veins of this class are usually associated closely with igneous rocks; some of them are inclosed in walls of igneous rock; others are in sedimentary beds near igneous rocks. The igneous rocks to which they are genetically related range from acidic to basic but are mostly either intermediate in composition (diorites, diorite porphyries) or grade toward the acidic end of the series (granites, alaskites, granodiorites, monzonites, quartz porphyries). A considerable number of these deposits, however, are genetically related to basic rocks.

Many of the deposits were formed at considerable distances from igneous rocks. In general they were deposited at greater

distances from the sources of the solutions than contact-metamorphic deposits and deposits of the deep vein zone.

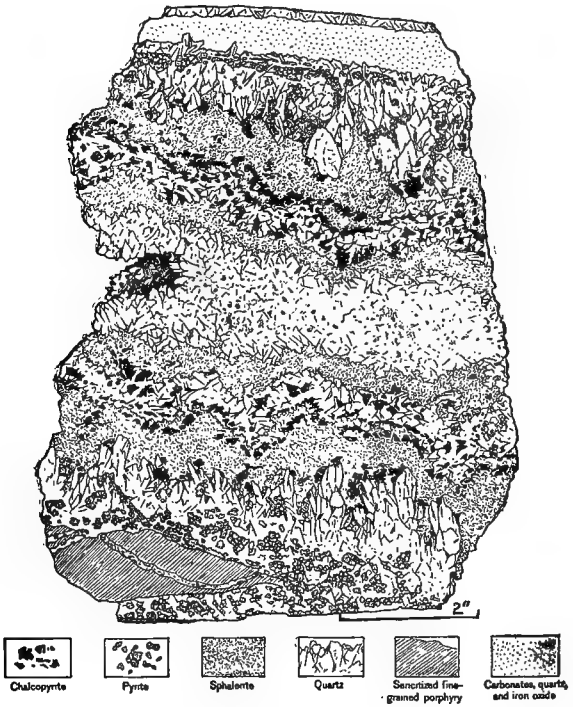


FIG. 137.—Section of banded vein, Pinos Altos district, New Mexico. (*After Paige, U. S. Geol. Survey.*)

Certain minerals found in deposits formed at moderate depths by hot solutions are listed below. In this list some secondary sulphides are included. Besides these there are many minerals formed by decomposition in the oxidizing zone.

apatite	chlorite	orpiment	rhodonite
argentite	cobaltite	pentlandite	sericite
arsenopyrite	covellite	petzite	siderite
barite	dolomite	platinum	stephanite
bismuth	enargite	polybasite	stibnite
bismuthinite	fluorite	proustite	sylvanite
bornite	galena	pyrargyrite	tellurides
calcite	gold	pyrite	tennantite
celestite	molybdenite	quartz	tetrahedrite
chalcocite	muscovite	realgar	tungstates
chalcopyrite	niccolite	rhodochrosite	zinc blende

Because the deposits have formed in and along fissures they are generally tabular, although many of them are irregular. Stockworks and disseminated deposits are developed also. In this group of deposits banding is very common, yet it is not universal. Although many of the deposits fill fissures, there is generally also pronounced replacement of the wall rocks by ore and gangue minerals. Symmetrically banded ore is commonly developed (Fig. 137). The deposits are typical of the depths where rocks are readily fractured; consequently the ore is frequently brecciated and recemented by ore of somewhat later age. The fissures are generally well defined, and many of them probably connected freely with the surface when they were metallized. In some districts contact-metamorphic deposits and deposits of the deep vein zone are found at the same elevation at which veins of the intermediate-zone type are developed. The solutions that deposited the contact-metamorphic deposits and the veins of the deep-zone type were probably under greater pressure because they were in restricted openings and could not move freely toward the surface.

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DEPOSITS FORMED AT SHALLOW DEPTHS BY HOT SOLUTIONS

Occurrence.—In igneous and sedimentary rocks. Many are in or near intrusive rocks consolidated at shallow depths. Common in regions of late igneous activity, especially in or near Miocene and later intrusives; in rocks that have not been deeply eroded since the ores were deposited.

Composition.—Minerals include simple sulphides, such as pyrite, sphalerite, galena, chalcopyrite, stibnite, and cinnabar, with the tellurides, selenides, and complex antimony and arsenic sulphosalts. Fluorite, chalcedony, adularia, barite, carbonates, and alunite are commonly present. The metals include gold, silver, quicksilver, antimony, arsenic, tungsten, lead, and zinc. Copper is a valuable constituent of zeolitic deposits but in North America is rarely present in large quantities in sulphide ores formed at shallow depths.

Shape.—Many are simple tabular fissure veins. Ledges and irregular replacement deposits are developed in shattered rocks. Irregular veins with ore chambers are characteristic, but bedding-plane deposits and saddles are less common than among the deposits formed at moderate depths.

Size.—Some deposits are small; others are large. Bonanzas are frequently found in the low-grade ore.

Texture.—Comb structure and crustified banding are common; vugs are nearly always present; many deposits are formed by replacement. Although hydrothermal alteration of country rock is usually extensive, the ore is generally deposited in or relatively near the fractures. In many districts lamellar quartz is developed in cleavage cracks of calcite, and when the calcite is dissolved it releases a quartzose ore with peculiar interpenetrating blades.

Deposits formed at shallow depths by hot solutions constitute one of the most valuable classes of ore deposits. They have produced a large part of the world's silver and considerable amounts of gold. The zeolitic copper lodes that are here included are among the most valuable sources of copper. Nearly all the quicksilver produced is obtained from deposits of this group, and also a little lead and zinc. These deposits naturally are not set off by sharp dividing lines from deposits formed at moderate depths, and there are numerous transitional types.

The deposits are found in all kinds of igneous rocks—acidic and basic, granular and glassy—also in sedimentary rocks. Generally they are in or near masses of intruding rocks. In the American Cordillera they are associated at a great many places with intrusive porphyries and andesites. Most of those found in flows or in sedimentary beds are not far from intrusive masses. Structurally nearly all the deposits of sulphide ores are fissure fillings or formed by replacement along fissures. Bedding-plane sulphide deposits, though not unknown, are rare in this class.

The deposits are formed in the upper zones where there is free connection with the surface, and therefore at low pressures and at relatively low temperatures. At shallow depths, where water columns are short and pressures low, the temperature of water solutions could not be very high, otherwise the solutions

would flash into steam and rise to the surface. Some of the minerals characteristic of the deposits are listed below. Some sulphides, generally secondary, are included.

adularia	chalcedony	magnesite	silver
alunite	chalcopyrite	marcasite	stephanite
analcite	chert	molybdenite	stibnite
ankerite	chlorite	polybasite	stilbite
arsenopyrite	cinnabar	proustite	sylvanite
barite	copper	pyrargyrite	tungstates
bismuthinite	dolomite	pyrite	tellurides
bornite	fluorite	quartz	tennantite
calaverite	galena	rhodochrosite	tetrahedrite
calcite	gold	realgar	zeolites
celestite	kaolin	sericite	zinc blende

Comparison of this list with those stating minerals formed in other deposits shows that some minerals are persistent—that is,

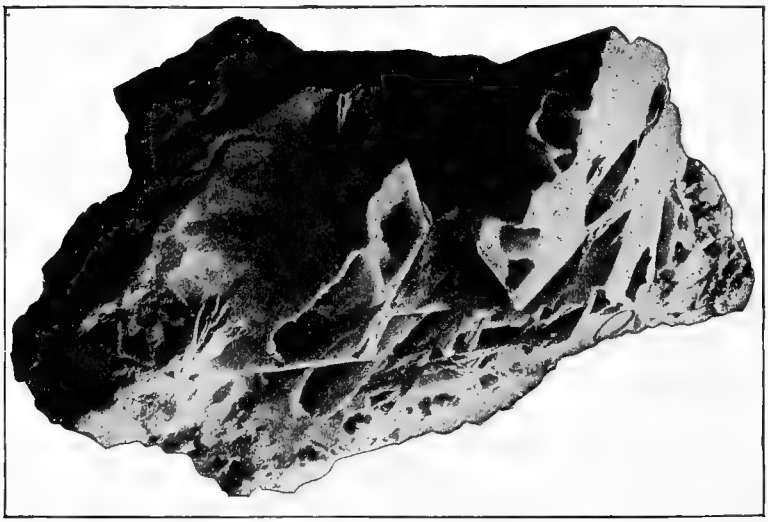


FIG. 138.—Ore from De Lamar mine, De Lamar, Idaho. The quartz blades filled cracks of calcite or barite, which subsequently was dissolved. (*After Lindgren, U. S. Geol. Survey.*)

they are found in deposits of several groups. A single mineral is rarely generically significant; groups of minerals generally are.

Some deposits of this group are small; others are very large. Many of the deposits are very rich—indeed, this class of primary or hypogene deposits may be characterized as the "bonanza" group. Near the surface ascending hot solutions mingle more

freely with cold ground water. The effect of cooling, decrease of pressure, and the mingling of solutions of different character all cause extensive precipitation.

The texture of the deposits of this group is in the main like that of lode formed at moderate depths. Vugs are perhaps more common. In many deposits chalcedony and quartz form bands of striking beauty. A structure common in calcite ores in several deposits in the Western States shows blades of quartz joining at angles similar to the cleavage angles of calcite. Such ores are found at De Lamar, Idaho (Fig. 138); Marysville, Mont.; Bullfrog and Manhattan, Nev.; and in other districts. The calcite, after it was formed, was filled by small veinlets of quartz occupying the cleavage planes and locally cutting across the crystals from one plane to another. After the lime carbonate is dissolved, the thin blades of silica remain as pseudomorphs of the calcite cleavage. Where the calcite is manganiferous many of the blades of silica are coated by sooty manganese oxide, locally carrying gold.

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DEPOSITS FORMED AT MODERATE AND SHALLOW DEPTHS BY COLD METEORIC WATERS

Occurrence.—Mainly in sedimentary rocks—limestones, shales, and sandstones. Organic matter or other reducing agents are commonly present in noteworthy amounts. Many of the valuable minerals occur in solution cavities and in zones of brecciation and subordinately in fissures and faults. Some are formed by replacement.

Composition.—The principal minerals are sulphides of zinc, lead, iron, and copper, with their alteration products and oxides of iron and manganese. Gangue minerals include calcite, chert, dolomite, jasper, barite. Mineral simplicity is characteristic. Heavy silicates are absent, and complex antimony, arsenic, selenium, and tellurium minerals are rarely if ever present. Nonmetals include asbestos, talc, magnesite barite quartz, phosphate and nitrates. The metals include lead, zinc, copper, uranium, vanadium, iron, and manganese.

Shape.—Large tabular upright bodies like some of the fissure veins genetically related to igneous rocks are very rare, but "sheet ground" is developed in bedding planes, forming extensive tabular ore bodies. Crevices, gash veins, runs, or flats and pitches are characteristic in some districts. Many of the deposits are very irregular, especially those that fill solution cavities.

Size.—Some of the bedding-plane deposits, the disseminated lead deposits of southeastern Missouri, and deposits in "sheet-ground" in the Joplin district, are very large. The larger bodies are parallel to bedding planes and in rocks not tilted are flat-lying. Many of the deposits are small.

Texture.—Solution cavities, crustified banding, and symmetrically lined vugs are common, but the regularly banded quartz veins so conspicuous among deposits genetically related to igneous rocks are rare. Brecciated structure is common. In some districts "disseminated ore" is developed, the metallic sulphides being sparingly but somewhat regularly distributed through great bodies of rock.

Much lead and zinc, some iron and manganese, and a little copper are supplied by deposits formed at moderate and shallow depths by cold meteoric waters. The lead and zinc deposits of the Mississippi Valley are the chief representatives of this class in North America Many of the deposits of this class are far removed from igneous rocks; some are more than 100 miles away.

It appears improbable that buried igneous rocks, contemporaneous with or later than the formations that contain the ore are concealed below the surface, near enough to the zone of fracture for magmas to have contributed water or mineral salts to the areas containing these deposits, for the mineralized areas are large, and extensive igneous activity would probably be attended by the eruption of lavas at one place or another. It is unlikely

also that intrusives many miles away have contributed the metals. In the West, where the larger ore deposits are almost invariably associated with igneous rocks, they are generally in or grouped closely around intrusives. Only exceptionally are they as far as one mile from outcrops of igneous rocks.

As the solutions that formed these deposits[1] were meteoric waters, not heated by igneous rocks, they were cold or at least not warmer than meteoric ground water would become by circulating through rocks that probably have the normal heat gradient for the earth, which is about 1°C. for 30 meters. As the waters were cold, the country rock has suffered no hydrothermal metamorphism, and those changes which ithas undergone are characteristic of weathering. As the solutions are cold, precipitation is brought about by changes in chemical environment, rather than by great changes in temperature. Bituminous limestones and carbonaceous shales and sandstones are especially favorable for the development of deposits of this class.

In the Southwest many copper deposits occur in sandstone and shale far removed from igneous rocks.[2] The principal ore minerals are chalcocite and bornite, which occur in a gangue of barite, calcite, and subordinate quartz. The copper sulphide in some deposits is precipitated on coal and other carbonaceous material (Fig 139). The associated beds in many places contain sulphates and chlorides, and it is supposed that the copper was dissolved out of the rocks and concentrated in beds and along fissures, where precipitation was favored by the presence of organic matter.

The precipitation of the metals by organic matter is not the only way in which precipitation may be accomplished. Small amounts of lead and zinc sulphide may be dissolved by carbonic acid, the process yielding lead and zinc carbonates and hydrogen

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[2] Emmons, S. F.: Copper in the Red Beds of the Colorado Plateau Region. U. S. Geol. Survey *Bull.* 260, pp. 221–232, 1905.

sulphide.[1] In depth in the presence of carbon dioxide the metallic sulphides are not precipitated, but when the solutions rise again near to the surface carbon dioxide escapes, and the metals are deposited as sulphides.

Iron dissolved from country rock in sulphate or carbonate solutions may be precipitated as oxide by descending waters. At many places, small veins are deposited in fissures or replace the rock along fissures. Manganese, under some conditions at least, is dissolved more readily than iron. It is easily precipi-



Fig. 139.—Section of chalcocite (light) replacing coal (dark), Nacimiento district, New Mexico. Upper part of specimen is altered by oxidation. (*Redrawn from plate by Lindgren, Graton, and Gordon, U. S. Geol. Survey.*)

tated as oxide when acid solutions are neutralized by alkaline rocks.

Some of the minerals that are found in deposits of this class are listed below. Of these, many are confined to oxidized zones

alum	chalcedony	greenockite	quartz
anglesite	chalcocite	gypsum	rhodochrosite
aurichalcite	chalcopyrite	hematite	selenite
azurite	chert	kaolin	siderite
barite	chrysocolla	limonite	smithsonite
bauxite	copper	malachite	sulphur
bornite	covellite	marcasite	uranium compounds
calamine	dolomite	millerite	vanadium compounds
calcite	fluorite	psilomelane	zinc blende
celestite	galena	pyrite	
cerussite	gold	pyrolusite	

[1] Siebenthal, C. E: Origin of the Zinc and Lead Deposits of the Joplin Region, Missouri, Kansas, and Oklahoma. U. S. Geol. Survey *Bull.* 606, p. 142, 1915.

near the surface and are regarded as alteration products of primary minerals. In this group of deposits it is not always easy to distinguish between primary and secondary ores.

The large tabular upright ore bodies that are commonly referred to as "true fissure veins" are conspicuous in many districts where the ores are genetically related to igneous rocks but are rare in regions where the deposits were formed by cold meteoric waters. Extensive bedding-plane deposits are formed in such regions; the Joplin district of southwestern Missouri and the lead district of southeastern Missouri contain bedding-plane deposits that are as large as the great veins above mentioned. Where deposits have been formed in ancient underground water channels they may be followed here and there over distances of several miles. A great many deposits of this group, however, are small.

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SEDIMENTARY DEPOSITS

Occurrence.—In sedimentary rocks—gravels, sands, clays, conglomerates, sandstones, shales, etc.—usually as beds or parts of beds, or disseminated through certain beds. All are oriented with the contemporaneous strata. Where they have not been disturbed they are flat-lying.

Composition.—In the clastic sedimentary deposits the minerals are the residual or stable minerals of older rocks and older deposits. They include gold, platinum, iron, tin, rutile, zircon, rare-earth minerals, gems, and other relatively insoluble materials. In beds which are chemical precipitates iron and manganese are the most important metals. Nonmetallic substances are coal, oil shale, petroleum, phosphate rock, common salt, potash salts, gypsum, clays, and many other materials.

Shape.—In general two dimensions are great and one is relatively small. Some placers are long in one and short in two dimensions. Equidimensional deposits are rare but not unknown.

Size.—Some are small; others are very extensive. Among the latter are certain beds of coal, gypsum, salt, and phosphate.

Texture.—Some deposits of this class have a structure characteristic of sedimentary rocks, such as is produced by sorting in water—bedding, cross-bedding, etc. In some the constituent particles are rounded by wear. Some contain fossil remains. Included anisodiametric bodies deposited mechanically with the beds are generally oriented with their short dimensions across the beds. The chemical sediments may be oolitic, crystalline, or amorphous. Banded structure is common but is rarely symmetrical and is not crustified. Comb structure and vugs lined symmetrically with banded crusts are never present except where infiltration has taken place since the deposits were formed.

Sedimentary beds form one of the most productive sources of mineral deposits. They supply most of the coal, petroleum, phosphate rock, limestone, gypsum, cement rock, salts, and clays and many of the building stones and fluxes. Large quantities of iron, aluminum, manganese, gold, tin, tungsten, and chromium are derived from sedimentary beds. They are also important as sources of gems.

Many rocks contain valuable minerals in quantities so small that they are not workable. Weathering, erosion and transportation are processes of mineral segregation. A quartz diorite which has about the composition of the average igneous rock is composed of potash and lime-soda feldspars, quartz, muscovite, biotite, magnetite, augite, and other ferromagnesian minerals, and some minor constituents, such as titanite, apatite and pyrite. Normal weathering will tend to convert the rock to kaolin, quartz, and limonite; wad and bauxite also may form. With these "end products" of weathering titanite and some apatite

will remain. Ground water, which generally contains carbon dioxide, will dissolve and carry away alkalies and alkaline earths as carbonates or bicarbonates; the sulphur is converted to sulphates. Some iron, aluminum, and silica also are dissolved, but more slowly than the alkalies and alkaline earths. Phosphorus compounds and titanium dissolve slowly. The dissolved materials will be carried to the sea and form organic deposits

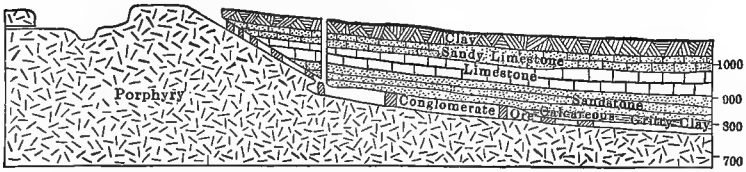


FIG. 140.—Section showing iron-ore deposits of Iron Mountain, Missouri. The iron has been quarried from openings at the top of the hill and mined underground at the base of the sedimentary series, where it formed a basal conglomerate. (*After Crane, Mo. Geol. Survey.*)

and chemical precipitates. Thus are supplied materials for beds of limestone, dolomite, chert, iron-bearing sediments, gypsum, phosphate rock, etc. The waters also carry in suspension or roll along their courses quartz, kaolin, limonite, and any heavy residual materials that may be present.

If the rocks decomposed contain deposits of metals, such as

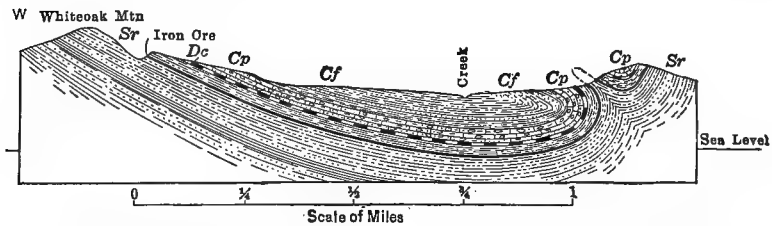


FIG. 141.—Section across Whiteoak Mountain syncline, Chattanooga, Tenn., showing "Rockwood" or Trenton iron-ore bed. *Sr*, "Rockwood" formation; *Dc*, Chattanooga shale; *Cp*, Fort Payne chert; *Cf*, Floyd shale. (*After Burchard, U. S. Geol. Survey.*)

copper, zinc, tin, and platinum, the soluble metals like copper and zinc may be carried downward and reprecipitated, or they may be carried to the sea and subsequently be precipitated there. The heavy, insoluble minerals, if any happen to be present, especially those which resist surface decomposition, like platinum, gold, and tin oxide, will generally be left behind in the beds of the streams not far from their outcrops.

Every constituent of the quartz diorite has a certain economic value if sufficiently concentrated, and when conditions are favorable many products may result from the processes of weathering, transportation, and deposition. But erosion seldom permits complete weathering, and the material, which is generally disintegrated mechanically before it is thoroughly decomposed chemically, passes to the sea in various stages of segregation.

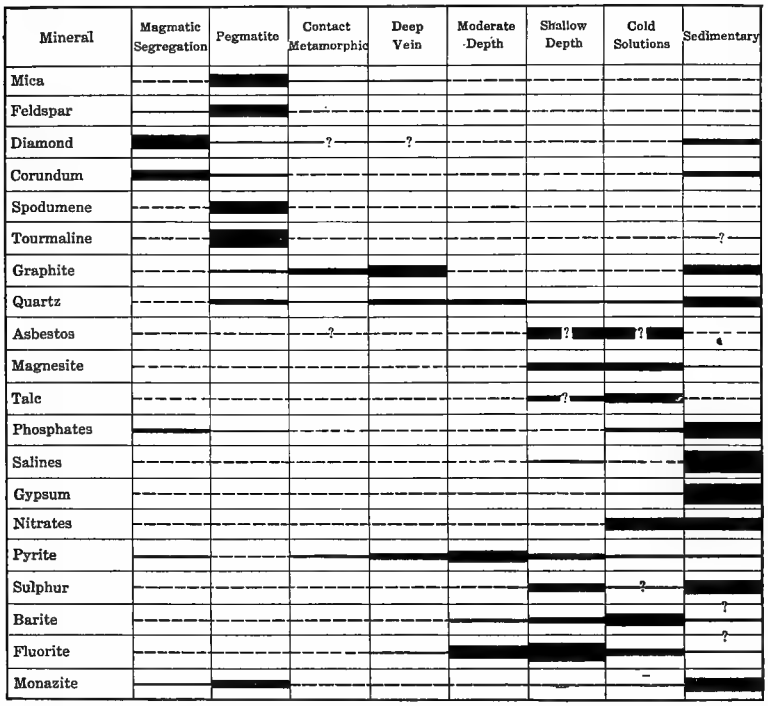


FIG. 142.—Diagram showing approximately the relative abundance of valuable deposits of certain non-metallic minerals grouped in the eight classes of primary deposits. The relative value of the deposits is indicated approximately by width of line. Broken lines indicate that the classes are of little or no value.

Thus the products of decomposition are generally found in various stages of impurity.

Sedimentary deposits may be divided into those concentrated mechanically (Fig. 140) and those concentrated chemically (Fig. 141). Deposits concentrated mechanically include basal conglomerates of iron ore, and the placers of platinum, gold, tin, etc. These deposits are marine, lacustrine, or fluviatile, the classification depending on the nature of the body of water in which they

have found rest. Deposits may be concentrated chemically as a result of evaporation, reduction, or oxidation, or by organic agencies. Examples of these are salt beds, coal, gypsum, and some iron ores.

Many deposits of sedimentary origin are workable in their primary state. Others supply the protores, which are further concentrated by weathering into workable ore bodies.

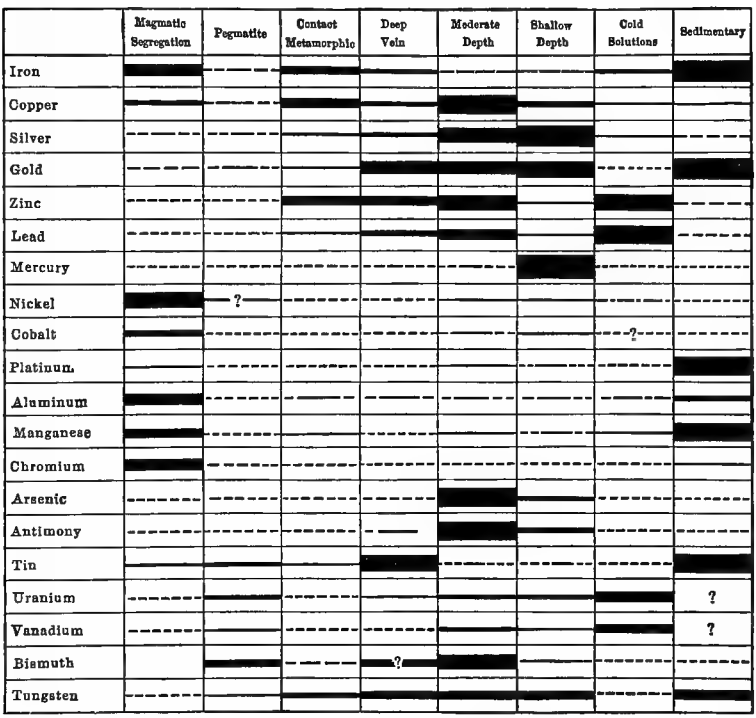


FIG. 143.—Diagram showing approximately the relative abundance of various classes of primary ores and protores of several metals. Broken lines indicate that classes of deposits are of little or no value. Broken lines with long dashes indicate rare deposits or deposits of subordinate value. Solid lines indicate valuable deposits—the value of the class being shown approximately by the width of the line.

Some sedimentary deposits are superficial—that is, they are not covered by later formations. Examples are bog-iron deposits, some beds of salt, borax, nitrates, and surface placers. Other deposits of this class, after they are formed, are buried below later sediments or igneous flows.

On the preceding pages of this chapter the chief characteristics of the deposits of the eight classes of primary ores and protores are outlined. Figures 142 and 143 show the importance of each class for many of the nonmetals and metals. In the following chapter the deformation and surface alteration of the deposits are taken up.

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CHAPTER VII

DEFORMATION AND ENRICHMENT OF MINERAL DEPOSITS

DEFORMATION OF MINERAL DEPOSITS

In the study of the genesis of a deposit three groups of processes should be considered—the deposition of the ore or protore, its deformation, and its superficial alteration and enrichment.

Many deposits, however, have not been deformed, and a considerable number are not appreciably enriched by superficial alteration. Some deformed deposits and some that are not deformed are workable, though superficial enrichment has not enhanced their value. Other ore bodies after their deposition have been both deformed and enriched.

Deformation is essentially a physical process, involving mass movement, but it may be attended by some chemical changes. Superficial alteration and enrichment are in the main chemical processes, involving molecular movement, although some mass movement may attend chemical changes. The deformation of ore deposits is merely incidental to the deformation of the containing rocks.

The character of primary ore bodies depends in large measure on their depth at the time of their deposition. Depth is a factor no less important in deformation. The earth's crust may be regarded as divided into three zones, characterized by the nature of deformation—a zone of fracture near the surface, where all rocks will break; a zone of flowage below the surface, where even the stronger rocks are not strong enough to hold spaces open under the pressures that prevail; and a zone of combined fracture and flowage, between these two, where strong rocks break and weak ones flow. This conception of deformation has been developed principally by Van Hise and Leith.

Rocks differ greatly in crushing strength. Shales will flow at shallow depths; quartzites and igneous rocks are strong enough to hold fractures open several miles below the surface. The zone of combined fracture and flowage is of great extent, embracing most of the zone that comes under observation.

Faulting is characteristic of the zone of fracture, and in areas of rocks deformed at shallow depths normal faults are generally more common than reverse faults, although the latter are not unknown, even at the surface. In the zone of combined fracture and flowage thrust faulting or reverse faulting is conspicuously shown. In the zone of flowage close folding is characteristic. There are great areas in the United States where normal faulting is common and reverse faulting with folding is rare, and other areas where folding and thrust faulting are common and normal faulting is practically unknown Thus there are deformation provinces, each characterized by a certain type of deformation, just as there are petrographic provinces and metallogenic provinces.

Faulting of Mineral Deposits.—Fault problems are common in applied geology because many mineral deposits, whatever their origin, are displaced by faults.

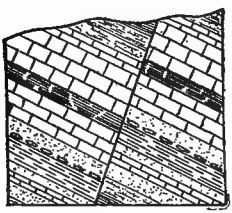


FIG. 144.—Normal fault.

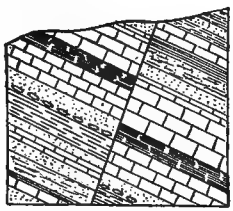


FIG. 145.—Reverse fault.

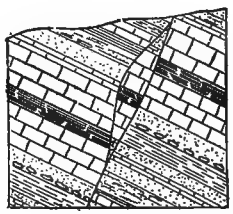


FIG. 146.—Horse in fault.

A *fault* is a fracture along which there has been notable displacement. Any fracture is accompanied by some movement, otherwise there would not be a fracture; but the term "fault" is not applied to movements at right angles to a fracture plane, but only to those where it can be shown that one or the other wall has been moved along the fracture plane (see Figs. 144, 145, 146).

The *fault strike* is the direction of the intersection of the fault surface with a horizontal plane—that is, a level line along a fault plane. The *fault dip* is the inclination of the fault surface measured at right angles to the strike on the plane of the fault. The *hade* is the inclination of the fault surface, measured from the vertical; it is the complement of the dip. The *hanging wall* is the upper wall of the fault. The *foot wall* is the lower wall of the fault. A fault block may move perpendicular to the strike of a fault plane, or parallel to it, or its path may make an acute angle with the strike. If one part of the block moves

farther in a given direction than another part, the block is said to *rotate*.

A *strike fault* is one whose strike is parallel to the strike of the strata. A *dip fault* is one whose strike is approximately at right angles to the strike of the strata. An *oblique fault* is one whose strike is oblique to the strike of the strata. A *bedding-plane fault* is one whose surface is parallel with the bedding of the stratified rocks.

The *separation* of the bed or vein or of any recognizable plane is the distance between the corresponding surfaces of the disrupted bed or other tabular body, measured between corresponding surfaces on the two sides of the fault, in any indicated direction. The *vertical separation* is the separation measured along a vertical line. The *horizontal separation* is the separation measured in any indicated horizontal direction.

The *normal horizontal separation* of a bed or other surface is its horizontal separation measured at right angles to the strike of the bed. It is frequently determined from the outcrops of the bed at the surface of the ground, and is then usually called the offset of the bed.

Normal faults are those along which the hanging wall appears to have been depressed relatively to the foot wall.

Reverse faults are those along which the hanging wall appears to have been raised relatively to the foot wall.

The terms "normal" and "reverse" designate the apparent displacement of the two parts of a dislocated bed or other recognized surface in a vertical plane at right angles to the fault strike.

Overthrusts are reverse faults with low dip. In some overthrusts the dip slip is great, amounting to several miles.

A *fault block* is a mass bounded on its sides, completely or in part, by faults. A *horst* is a mass elevated relatively to the surrounding masses and separated from them by faults. A *graben* is a mass depressed relatively to the surrounding masses and separated from them by faults.

A *fault mosaic* is an area divided by intersecting faults into blocks that have settled in varying degrees.

Fault striæ are scratches on the walls of faults formed by abrasion of hard particles. Striæ show the direction of movement along the walls. All the faulting movement may not have been in the direction indicated by the striæ; obviously the last move-

ment only may be recorded. On some faults two sets of striæ cross, showing different movements at different times. *Fault grooves* are undulations deeper than striæ but similarly formed. Because they usually record larger stresses they have greater significance as indicating direction of movement.

If faulting has dislocated a homogeneous body—for example, a great uniform mass of igneous rock—it may not be possible to show even approximately how much movement has taken place. The walls of fissures may be striated or scratched by hard particles rubbing against them, or they may be "case-hardened" or "slickensided" by attrition, or rounded boulders or friction breccia may be found in and along the fissures. All

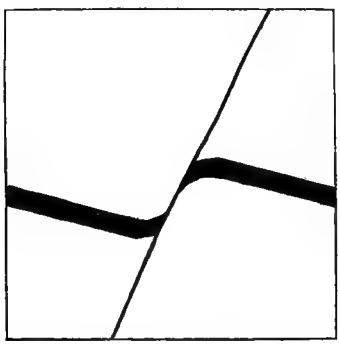


FIG. 147.—Vein curved near fault.

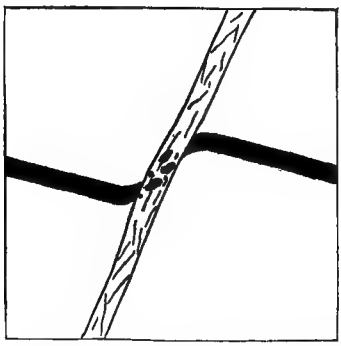


FIG. 148.—Drag ore along fault zone.

these features suggest that there has been movement parallel to the fissure, although it is not possible to prove any displacement because there are no horizons of reference.

Some faults are curved near the break, and the curve will frequently show the direction of movement (Fig. 147). In one direction from the ore body the fault zone may carry "drag ore" or crushed and brecciated vein matter (Fig. 148), whereas in the other direction it may be barren. Thus drag ore may lead to a lost segment. On many faults, however, the vein is not curved near the break, and on some no drag ore is shown; still others show drag ore along the fault in both directions as it is followed away from the ore body.

Folding of Mineral Deposits.—When rocks are broken in blocks and faulted, they are generally tilted and commonly they are flexed or folded. Rocks may be folded in the zone of fracture by movement along many small faults or along joints. This is

commonly the case where brittle rocks are deformed near the surface. If rocks containing ore deposits are folded in the zone of fracture, any deposits of brittle minerals they contain, such as quartz, will be folded by fracture.

When rocks are folded in the zone of flowage there is a movement of their minute particles attended by recrystallization and changes in the thickness of the beds.[1] In the zone of flowage the mineral character of the beds or deposits is generally extensively altered. These changes, due to folding in the zone of flowage and recrystallization, are phenomena attending dynamic metamorphism of the rock or ore body. Folding may take place without dynamic metamorphism, but dynamic metamorphism is practically always attended by much folding.

Dynamic Metamorphism of Mineral Deposits.—Any mineral deposit, however formed, may be metamorphosed by dynamic processes.

Rocks that are deeply buried are held down by the superincumbent load and can not move about so freely as independent blocks. At great depths, or where the overlying load is sufficiently heavy, the stresses are greater than the crushing strengths of the rocks, which, however, vary greatly, as is shown by the following table:

	Pounds per square inch
Granite	15,000 to 30,000
Sandstone	8,000 to 12,000
Limestone	3,000 to 14,000
Shale	1,000 to 3,000
Clay and mud	0 to 500

Strong granite, which weighs about 165 pounds a cubic foot, is rigid enough to bear a mass of granite about 5 miles high. If factors like differential strains and the weakness of mortar are disregarded, a block of granite in the lower course of a stone monument would theoretically bear the strain of the weight of 5 miles of granite above it. But if a sufficient weight were placed above it, the lower course would fail. Sandstone and limestone would fail under much lighter loads, and shale would fail under a load lighter still. When a rock is so deeply buried that the weight above it exceeds its crushing strength, open spaces or continuous fractures will be closed by the failure of the rock, which acts somewhat as a viscous mass and is said to be deformed by "flowage."

[1] LEITH, C. K.: "Structural Geology," p. 109, 1913.

At considerable depths rocks will hold spaces open under greater pressures than near the surface, because their openings may contain water, and the water pressure counterbalances some of the pressure on the rocks. When corrections are made for this factor and for increased rigidity due to lateral support,[1] it appears that while some shales may flow at depths less than 1,500 feet, the strongest rocks would probably not flow at depths of considerably more than 6 miles.[2] If a mass composed of several formations that differ in strength is deformed by pressure, some of the rocks may flow while others fracture (see Fig. 149). The rock mass is then in the zone of combined fracture and flowage.[3] This is a wide zone; as already stated, some clays and

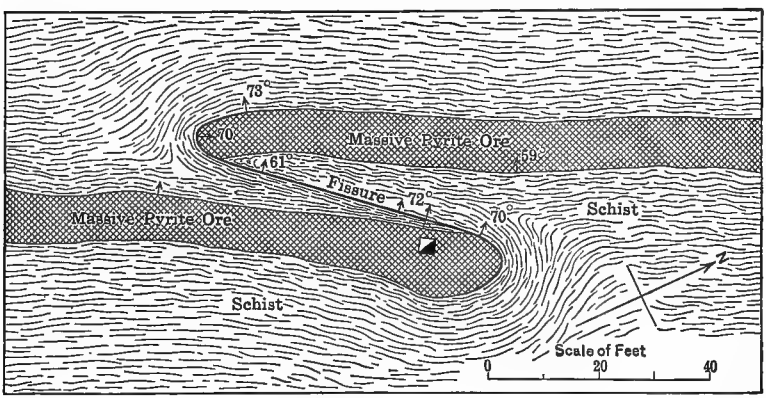


FIG. 149.—Plan of part of 115-foot level, Milan mine, New Hampshire. The pyritic quartzose copper ore fractured while the mica schist "flowed."

shales will flow almost at the surface, but granite and other strong rocks might fracture rather than flow at depths of several miles. Very commonly masses composed of rocks of two or more kinds will, after deformation by pressure under load, exhibit structure characteristically found in the zone of combined fracture and flowage. The crushing strength of ore bodies depends upon the component minerals and their arrangement.

[1] ADAMS, F. D.: An Experimental Contribution to the Question of the Depth of the Zone of Flowage in the Earth's Crust. *Jour. Geol.*, vol. 20, pp. 97–118, 1912.

[2] LEITH, C. K.: "Structural Geology," p. 3, 1913.

[3] VAN HISE, C. R.: A Treatise on Metamorphism. U. S. Geol. Survey *Mon.* 47, p. 748, 1904.

In general ore bodies are stronger than argillaceous rocks (see Fig. 149).

Rocks that are deformed under great load by pressure (anamorphism) undergo certain characteristic changes. The brittle minerals, such as quartz and feldspar, are mashed, cemented, and recrystallized. Mica, chlorite, and amphibole are generally developed. These platy or fibrous minerals are arranged generally with their long dimension normal to the direction of greatest pressure, thus giving the rock schistosity[1] or slaty cleavage (see Fig. 150). Extensive recrystallization may take place, with the development of garnet, staurolite, ottrelite, andalusite, and other heavy silicates. These minerals are sometimes called the "porphyritic minerals" of schist, and in many schistose rocks they are not arranged parallel to the schistosity.

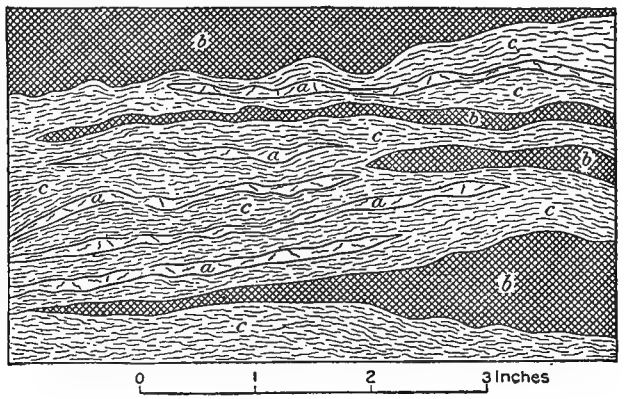


FIG. 150.—Sulphide ore metamorphosed by pressure. *a*, Quartz; *b*, pyrite; *c*, chlorite schist.

When ore bodies under load are subjected to heavy stresses great changes may take place, but they probably do not involve the introduction of large amounts of material. This view is not shared by those who regard the "segregated vein" as a body of ore brought together during dynamic metamorphism by solutions searching great masses of rock and concentrating in a smaller mass the metals which before metamorphism were widely scattered through the great masses.

[1] WILLIS, BAILEY: The Mechanics of Appalachian Structure. U. S. Geol. Survey *Thirteenth Ann. Rept.*, part 2, pp. 211–281, 1892.

Bastin[1] has made averages of hundreds of analyses of shales, slates, pelites, and schists and found certain clearly expressed chemical relations which recur throughout the different series, exhibiting various degrees of metamorphism. His averages of analyses indicate that little material is added. The mineral changes are due to rearrangement[2] of the elements of the shale or slate rather than to the introduction of new elements. Although these investigations indicate that there is but little gain of material during dynamic metamorphism of aluminous sedimentary rocks, a loss of material may take place during metamorphism, especially losses of the more soluble substances, such as lime carbonate.

Although the ore[3] and gangue minerals have a greater crushing strength than the aluminous minerals of quartzitic shale and are therefore more competent to hold spaces open, the same principles will probably apply to them. The processes which operate in the regional or dynamic metamorphism of ore bodies are solution, reprecipitation, mashing, dehydration, deoxidation, and cementation. These changes are attended by the formation of complex minerals of high specific gravity that occupy less space than simple minerals. The elements are rearranged within the ore body; there may be losses, but probably little material is added. However, where igneous bodies intrude rocks at great depths under heavy load, igneous metamorphism may take place, and it may be attended by the addition of much material. Some investigators believe that waters from deep sources migrate considerable distances through rocks deeply buried in the zone of flowage. The changes in composition of coals due to loss of volatile hydrocarbons during metamorphism have been mentioned (p. 17).

As deposits of any character may be metamorphosed by pressure, the metamorphosed deposits contain a great variety of minerals. Many of these minerals were doubtless formed by primary processes and have endured throughout the metamorphic changes, but others have been formed while the deposits have

[1] Bastin, E. S.: Chemical Composition as a Criterion in Identifying Metamorphosed Sediments. *Jour. Geol.*, vol. 17, pp. 445–472, 1909.

[2] Leith, C. K., and Mead, W. J.: "Metamorphic Geology," pp. 161–168, 1915.

[3] Uglow, W. L.: Gneissic Galena Ore from the Slocan District, British Columbia. *Econ. Geol.*, vol. 12, pp. 643–662, 1917.

been deeply buried and compressed. Garnet, chlorite, epidote, zoisite, mica, and amphibole are very commonly present. Even if they do not occur in the primary deposits, one or all of them may be formed during metamorphism. The sulphides are probably little changed, at least in kind. By dehydration and reduction, hematite and magnetite are assumed to be developed. By some investigators pyrrhotite is believed to be characteristic of these deposits, but in some of the metamorphosed pyritic deposits it is lacking.

SUPERFICIAL ALTERATION AND ENRICHMENT OF MINERAL DEPOSITS

Rocks and ores exposed to air and water at or near the surface of the earth break down and form soluble salts and minerals that are stable under surface conditions. Few minerals that are long exposed to air and water remain unaltered; some, however, are much more resistant to weathering than others and these become concentrated when material associated with them is removed. Weathering usually precedes erosion, and many valuable beds, such as clay, sand, iron ore, and placer gold, become concentrated through weathering and aggradation working together.[1]

Weathering softens rocks and may make them more easily worked for any valuable minerals they contain. By weathering, many low-grade ores and protores are converted into valuable deposits. Enrichment may be brought about by solution and removal of valueless material, leaving the weathered material in a more concentrated state; or it may be brought about by solution of valuable materials and their precipitation in depth. Some metals are readily dissolved near the surface in oxygenated waters, and are readily precipitated at depths where air is excluded and where the acid solutions are rendered neutral by reacting on ores and rocks. Many sulphide deposits are leached of metals near the surface but are enriched near the water level where air is excluded and precipitation takes place.

[1] For more extended discussions of rock weathering the reader is referred to the following papers:

Merrill, G. P.: "Rocks, Rock Weathering, and Soils," 1897.

Van Hise, C. R.: A Treatise on Metamorphism. U. S. Geol. Survey *Mon.* 47, 1903.

Emmons, W. H.: The Enrichment of Ore Deposits. U. S. Geol. Survey *Bull.* 625, 1917.

A primary or hypogene deposit is one that is essentially unchanged by superficial agencies. A secondary or supergene deposit is one that has been altered by superficial agencies. The processes of weathering and also of sulphide enrichment are closely allied to the deposition of ore bodies at moderate depths by cold solutions. There is this difference, however: the ore bodies mentioned are formed at places where no metalliferous rock may have existed previously, and many though not all are formed at or near places where there was some reducing agent such as carbonaceous material. Metalliferous products of weathering and sulphide enrichment occupy in the main the spaces formerly occupied by lower-grade metalliferous material from which the workable deposits were derived.

WEATHERING OF ROCKS

The term weathering includes all the processes by which rocks near the surface exposed to water and air are gradually decomposed and broken up. These processes are active mainly above the water level. Rain water carries oxygen and some carbon dioxide, which render it an active solvent. The alkalies in rocks are readily dissolved, especially sodium. Alkaline earths are attacked also, and calcium and magnesium go into solution. Silica dissolves less readily, but the alkalies render the solutions more active solvents of silica. The metals iron and aluminum are slowly dissolved, iron in general more rapidly than aluminum. New minerals are formed, especially oxides, hydroxides, and carbonates; most carbonates, however, are unstable under conditions of thorough weathering.

Of the minerals attacked by weathering some are comparatively stable. Gold, platinum, magnetite, chromite, garnet, cassiterite, rutile, monazite, and several others are not readily dissolved and will accumulate in residual bodies, gravels and placers. Quartz is not strongly attacked, but the alkali, alkaline earth, and iron silicates dissolve more readily. As a general rule the silicates containing little silica, such as olivine and enstatite, will be changed more readily than feldspar, and feldspars more readily than quartz. Consequently the basic rocks—gabbro, peridotite, and others—are the more readily altered. Such rocks on weathering yield many metalliferous products (Fig. 151).

Thorough weathering may convert a basic rock to a mantle of workable iron ore. Such deposits are termed lateritic ores. In

eastern Cuba lateritic iron ores are extensively developed. The deposits cap intrusive bodies and are on plateaus 1,500 to 2,000 feet above sea level. The ore grades downward into serpentine, an altered basic intrusive rock containing a little bauxite, kaolin, and minerals. Leith and Mead[1] have calculated the mineral constituents of the ore and determined the amount of pore space at different depths. Below 29 feet serpentine is encountered. By the removal of magnesia and silica the pore space is much increased near the surface and the serpentine rock, which carries only 7.10 per cent. of iron, becomes an ore carrying 46.39 per cent. of iron. Ferruginous sedimentary rocks are converted to rich ores by weathering.

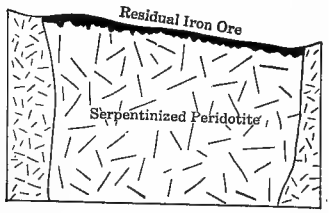


FIG. 151.—Cross-section of iron ore deposit formed by leaching valueless material from an igneous protore.

SUPERFICIAL ALTERATION AND ENRICHMENT OF SULPHIDE DEPOSITS

General Features.—Many sulphide deposits show characteristic changes from the surface downward.[2] The outcrop and

[1] LEITH, C. K., and MEAD, W. J.: Origin of the Iron Ore of Central and Northeastern Cuba. Am. Inst. Min. Eng. *Trans.*, vol. 42, pp. 90–102, 1912; vol 53, pp. 75–78, 1915.

[2] EMMONS, S. F.: The Secondary Enrichment of Ore Deposits. Am. Inst. Min. Eng. *Trans.*, vol. 30, pp. 177–217, 1901.

WEED, W. H.: The Enrichment of Gold and Silver Veins. *Idem*, pp. 424–448.

KEMP, J. F.: Secondary Enrichment in Ore Deposits of Copper. *Econ. Geol.*, vol. 1, pp. 11–25, 1906.

RANSOME, F. L.: Criteria of Downward Sulphide Enrichment. *Econ. Geol.*, vol. 5, p. 205, 1910.

PENROSE, R. A. F., JR.: The Superficial Alteration of Ore Deposits. *Jour. Geol.*, vol. 2, pp. 288–317, 1894.

TOLMAN, C. F.: Secondary Sulphide Enrichment. *Min. and Sci. Press.*, vol. 106, pp. 38–43, 141–145, 178–181, 1913.

EMMONS, W. H.: The Enrichment of Ore Deposits. U. S. Geol. Survey *Bull.* 625, pp. 1–503, 1917.

BASTIN, E. S: Metasomatism in Downward Sulphide Enrichment. *Econ. Geol.*, vol. 8, pp. 51–65, 1913.

GRATON, L. C., and MURDOCH, JOSEPH: The Sulphide Ores of Copper; Some Results of Microscopic Study (with discussion by James F. Kemp, Horace V. Winchell, and L. C. Graton). Am. Inst. Min. Eng., *Trans.* vol. 45, pp. 26–93, 1913.

the upper part of the oxidized portion of a deposit may be poor. Below this there may be rich oxidized ore; still farther down, rich sulphide ore; and below the rich sulphides, ore of relatively low grade (see Fig. 152). This lowest ore is commonly assumed to be the primary ore, from which the various kinds of ore above have been derived. The several kinds of ore have a rude zonal arrangement, the so-called zones being, like the water table, highly undulatory (see Fig. 153). They are related broadly to the present surface and generally to the hydrostatic level but may be much more irregular than either, for they depend in large measure on the local fracturing in the lode, which controls the circulation of underground waters. Any zone may be thick at one place and thin or even absent at another. The zone of oxidized ore is generally above the water level. The zone of secondary sulphides in moist countries is in general below the water level.

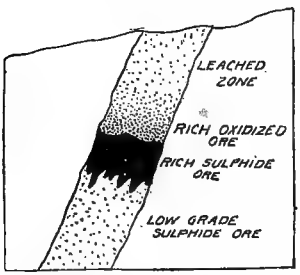


FIG. 152.—Section showing a tabular sulphide ore deposit with changes due to superficial alteration and enrichment.

All these zones except that of the primary ore are, broadly considered, continually descending. Through more rapid erosion

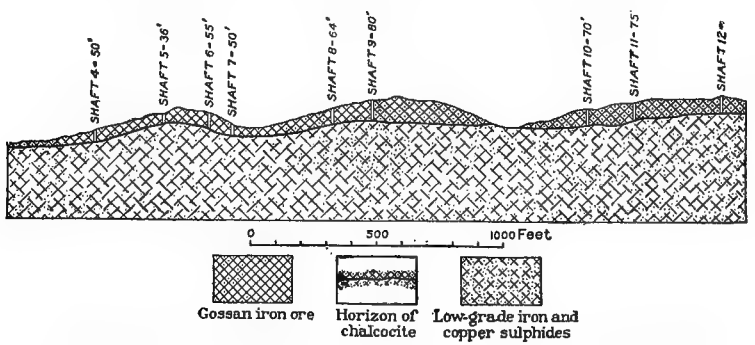


FIG. 153.—Longitudinal section of a part of the Old Tennessee-Cherokee lode, Ducktown, Tenn.

at some particular part of the lode any one of these zones may be exposed, and hence an outcrop of ore of any character is possible.

Level of Ground Water.—The terms "water table" and "level of ground water" are generally used to describe the upper limit of the zone in which the openings in rocks are filled with water.

This upper limit of the zone of saturation is not a plane but a warped surface. It follows in general the topography of the country but is less accentuated. It is not so deep below a valley as below a hill but rises with the country toward the hilltops.

Circulation of Water.—Of the rain that falls on the surface a part is drained off by rills and streams, another part is evaporated and still another part soaks deep into the ground, passes downward, and is added to the water of the zone of saturation. The downward movement of such water toward the zone of saturation has been termed the "vadose" circulation (from *vadus*, shallow). The vadose circulation is above the water level. Below that level, where openings are filled with water, there is a deeper circulation.

The circulation of the water in the zone of saturation depends on the relief of the country and on the number, continuity, spacing, and size of the openings in the rocks. Under hydrostatic head the waters in this zone move to points of less pressure and issue at points lower than those of entry. If the deposit is tight and there are no deep outlets the principal movement is shallow, following down the grade of the water table. As a rule movement in the deeper zone is much slower than in the vadose zone, because the openings are less numerous and also because they are smaller, so that friction on their walls is greater. Below the water table, moreover, the openings are already filled with water. Below the zone of deep circulation is one in which water is nearly stagnant.

Outcrops.—Nearly all deposits of sulphides carry pyrite, which upon oxidation yields limonite. Thus the outcrops[1] of most sulphide deposits carry iron oxides. In general, prospectors looking for sulphide ores of the metals seek an iron-stained outcrop in the hope that it may prove to be the top or gossan of a sulphide deposit. If the sulphide ore bodies carry large proportions of iron sulphide, the outcrops will invariably carry iron. In some deposits, however, copper sulphides replace iron sulphides in the secondary sulphide zone, and the oxidation product of a chalcocite zone may show very little iron oxide. Some bodies of copper ore have outcrops of light-colored kaolinized rocks that are not highly ferruginous.

[1] PENROSE, R. A. F., JR.: The Superficial Alteration of Ore Deposits. *Jour. Geol.*, vol. 2, pp. 298–317, 1894.

EMMONS, W. H.: Outcrops of Ore Bodies. In BAIN, H. F., and others: "Types of Ore Deposits," pp. 299–323, San Francisco, 1911.

Generally the outcrops of silver deposits carry silver. Some of them in arid countries, where silver chloride forms at the surface, carry more silver at and near the surface than below. Some gold ores, especially manganiferous gold ores, are leached near the surface; other gold deposits are commonly enriched by removal of material other than gold.

The Oxidized Zone.—The oxidized zone is in the main the zone of solution. Precipitation also takes place in this zone, especially the precipitation of the oxides or hydrous oxides of iron, aluminum, manganese, and silicon. By redeposition ores of the more valuable metals also are formed in this zone. Solution generally exceeds precipitation, however, and by solution the mass is reduced and open spaces are enlarged.

The Secondary Sulphide Zone.—The secondary sulphide zone lies below the oxidized zone. It is not everywhere developed,

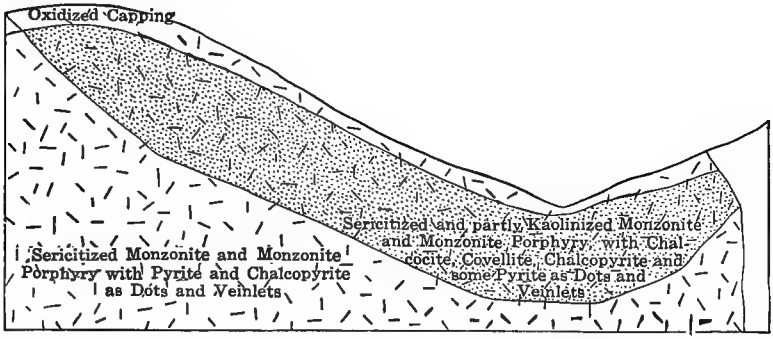


FIG. 154.—Section through disseminated copper deposit, Bingham, Utah. Based on maps published by Utah Copper Company.

not even in copper ores that are capped with gossan. In many deposits the transition between the oxidized and secondary sulphide zone is sharp, being essentially at the ground-water level. In such deposits the secondary ores extend downward to various distances below the water level. The vertical extent of the secondary zone differs widely in different districts. In some of the copper districts of the southern Appalachian region the chalcocite zones occupy only a few feet vertically. At Ducktown, Tenn., in all except one mine the average thickness of the secondary chalcocite zone is probably between 3 and 8 feet, but some secondary chalcopyrite is developed far below this zone. In the disseminated deposits in porphyry at Bingham, Utah, the zone of workable sulphides, mainly chalcocite, covellite, and

chalcopyrite, has an average vertical extent of 421 feet (Fig. 154). At Globe, Ariz., in the Old Dominion mine, chalcocite has been found more than 1,200 feet below the surface and has a vertical range of at least 800 feet. In silver deposits the secondary sulphide zone often lies deep (Fig. 155).

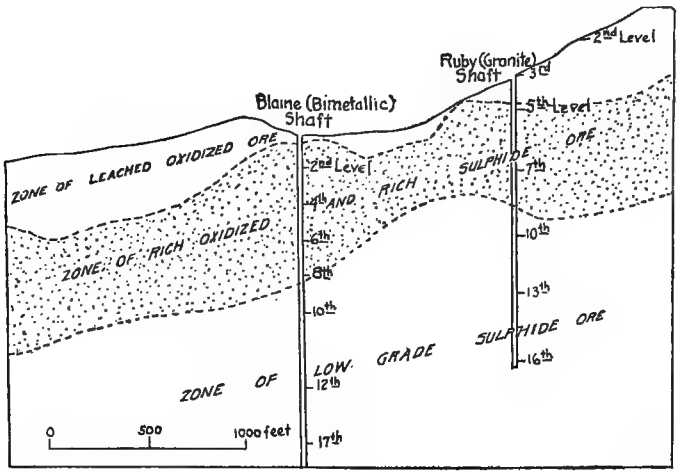


FIG. 155.—Vertical section of Granite-Bimetallic vein, Philipsburg, Montana.

Textures of Secondary Ores.—Oxidized ore is generally spongy and contains numerous cavities due to solution. The iron ores formed by the superficial weathering of ferruginous rocks are almost invariably open-textured, although in some deposits the pore space formed by the removal of valueless material is eliminated by slumping near the surface or by cementation with iron oxide at lower depths. Near the surface pyrite alters to limonite (Fig. 156). Gossans of sulphide ores contain many openings ranging in size from minute pores to enormous caves. Stalactites, stalagmites, nodules, and reniform bodies are characteristic. These forms consist principally of hydrous iron oxides, subordinately of carbonates and other compounds. Similar forms are almost unknown in sulphide ores deposited by hot solutions.

The solution of primary sulphides and the precipitation of secondary sulphides may go on simultaneously, the secondary minerals replacing the primary. Pseudomorphs of chalcocite or covellite after pyrite, chalcopyrite, or zinc blende, in which the later minerals have assumed the forms of the earlier minerals, are

common. Fig. 157 shows chalcocite replacing pyrite. Chalcocite, argentite, and other dark copper and silver minerals are frequently found as sooty amorphous powder coating firmer and more distinctly crystallized minerals.

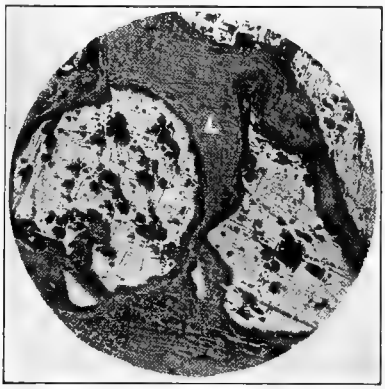


FIG. 156.—Polished surface of ore showing pyrite, *P*, partly replaced by limonite, *L*. From Old Dominion mine, Globe, Ariz. (*After G. M. Schwartz.*)

When some minerals have been dissolved, leaving other minerals intact, the empty spaces may be bounded by surfaces that represent former surfaces of dissolved crystals. Such spaces are

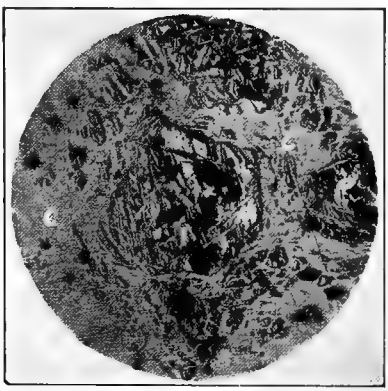


FIG. 157.—Polished surface of ore showing pyrite, *P*, partly replaced by chalcocite, *C*, from 12th level, Old Dominion mine, Globe, Ariz. Magnified 75 diameters. (*After G. M. Schwartz.*)

commonly developed in the gossan of quartz-pyrite deposits, especially where quartz predominates and surrounds the crystals of pyrite. Galena, tungstates, and many other minerals in

quartz will likewise be dissolved and leave their negative pseudomorphs.

Much of the material that is generally termed secondary sulphide ore consists essentially of shattered and fractured primary sulphide ore, the cracks in which are filled with later sulphides (Fig. 158) or with angular fragments of the earlier sulphides crusted over with those that were introduced later. Such tex-

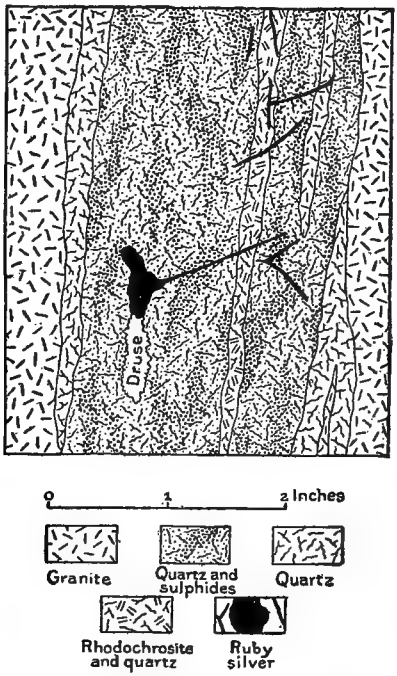


FIG. 158.—Banded ore from the South vein of the Granite-Bimetallic lode, Philipsburg, Mont. Secondary ruby silver is deposited in cross veinlets and vugs.

tures do not invariably indicate sulphide enrichment by descending solutions. Many examples show that in the course of primary mineralization the ore first deposited has been fractured and that solutions from below have deposited later sulphides in the fractures. If, however, the minerals that fill the later cracks are those that are commonly formed by descending solutions, and if they do not persist in depth, the assumption is warranted that they are secondary.

In some deposits the sulphides are intimately intergrown so that under the microscope their structure resembles that of graphic granite. Laney[1] first recognized such intergrowths in copper ores of the Virgilina district in Virginia and North Carolina (Fig. 159). Later similar intergrowths in copper ores were found in ores from many other mines. In general these intergrowths have been regarded as primary or hypogene.



FIG. 159.—Graphic intergrowth (primary) of chalcocite (light) and bornite (dark), Wall mine, Virgilina district, Virginia and North Carolina. (*After Laney.*)

Chemistry of Enrichment.—The chemistry of enrichment is complicated as to details, but the major features of the processes are simple. The metals enriched are dissolved in the solutions that are oxygenated and acid and are precipitated in solutions that are alkaline and reducing. All the iron sulphides yield acid readily. Pyrite,[2] the most common one, oxidizes as follows:

$$FeS_2 + 7O + H_2O = FeSO_4 + H_2SO_4$$

The ferrous sulphate is oxidized to ferric sulphate, which hydrolyzes, forming limonite and more sulphuric acid. Thus

[1] LANEY, F. B.: The Relation of Bornite and Chalcocite in Copper Ores of the Virgilina District, North Carolina and Virginia. *Econ. Geol.*, vol. 6, pp. 399–411, 1911.

[2] ALLEN, E. T.: Sulphides of Iron and Their Genesis. *Min. and Sci. Press*, vol. 103, pp. 413–414, 1911.

GOTTSCHALK, V. H., and BUEHLER, H. A., Oxidation of Sulphides. *Econ. Geol.*, vol. 7, pp. 15–34, 1912.

PENROSE, R. A. F., JR.: The Superficial Alteration of Ore Deposits. *Jour. Geol.*, vol. 2, p. 293, 1894.

WINCHELL, A. N.: The Oxidation of Pyrite. *Econ. Geol.*, vol. 2, pp. 290–294, 1907.

GROUT, F. F.: The Oxidation of Pyrite. *Econ. Geol.*, vol. 3, pp. 532–534, 1908.

BUEHLER, H. A., and GOTTSCHALK, V. H.: Oxidation of Sulphides. *Econ. Geol.*, vol. 5, pp. 28–35, 1910; vol. 7, pp. 15–34, 1912.

WELLS, R. C.: Electric Activity in Ore Deposits. U. S. Geol. Survey *Bull.* 548, pp. 1–78, 1914.

pyrite, pyrrhotite, and the copper-iron sulphides will yield much acid.

SOLUBILITIES OF SEVERAL SULPHIDES EXPRESSED AS MOLS PER LITER $\times 10^{-6}$

ZnS	70.600	PbS	3.600
FeS	70.100	CuS	3.510
CoS	41.620	As_2S_3	2.100
NiS	39.870	Ag_2S	0.552
CdS	9.000	HgS	0.054
Sb_2S_3	5.200		

Sulphuric acid readily dissolves copper, silver, zinc, and some other metals. Ferric sulphate increases solution. The solutions carrying the metals descend, and below the water level they are deposited. In general ground water that is in contact with rocks below the water level is alkaline. In depth, therefore, acidity is reduced and the metals are precipitated. The least soluble sulphides are most easily precipitated and will replace the more soluble ones metasomatically. Many crystals of sphalerite, pyrite, and galena are coated with copper sulphide, which they have evidently precipitated. These replacements are summarized in the table below.

METASOMATIC REPLACEMENT OF SEVERAL SULPHIDES

[In the order of Schuermann's series]

Mercury	Silver	Copper	Lead	Zinc	Iron
Mercury					
Silver		?	On PbS	On ZnS	On FeS_2
Copper			Metasomatic	Pseudomorphic	Pseudomorphic
Lead				On ZnS	On FeS_2
Zinc					"Drives out iron"
Iron					

ANALYSES OF MINE WATERS IN SULPHIDE DEPOSITS
(Part per million)

	1	2	3	4	5
SO_4	71,053.3	2,672.0	415.8	476.8	5,064
Cl	17.7	13.0	0.7	0.4	Undet.
CO_3					
PO_4	1.5	Trace			
B_4O_7	.....	Trace			
Br	.....	Trace			
F	.....	Trace			
SiO_2	67.4	47.7	37.0	49.9	76
K	6.8	13.1	2.7	2.2	Undet.
Na	41.7	39.6	5.2	5.5	
Li	Trace				
Ca	307.7	132.5	19.7	30.4	436
Mg	149.2	61.6	5.2	6.2	61
Al	85.2	83.5	14.5	19.1	Undet.
Mn	13.2	12.0	0.2	0.1	236
Ni	3.5	0.5			
Co	4.6				
Cu	45,633.2	59.1	28.1	11.0	1,659
Zn	411.2	852.0	2.4	2.9	Undet.
Cd	.....	41.1			
Fe″	49.8	159.8	71.4	89.2	305
Fe‴			20.3	55.9	
Acidity: H_2SO_4	.....	.....	210.2	97.5	970

1. Mountain View mine, Butte, Mont., second level. W. F. Hillebrand, analyst. CLARKE, F. W.: The Data of Geochemistry, 3d ed. U. S. Geol. Survey *Bull.* 616, p. 633, 1916.

WEED, W. H.: Geology and Ore Deposits of the Butte District, Montana. U. S. Geol. Survey *Prof. Paper* 74, p. 101, 1912.

2. St. Lawrence mine, Butte, Mont. W. F. Hillebrand, analyst.

CLARKE, F. W.: *Op. cit.*, p. 632.

WEED, W. H., *Op. cit.*, p. 101.

3. Callaway shaft, Ducktown, Tenn., at water level. R. C. Wells, analyst.

EMMONS, W. H. and LANEY, F. B.: Preliminary Report on the Mineral Deposits of Ducktown, Tenn., U. S. Geol. Survey *Bull.* 470, pp. 171–172, 1911.

4. Callaway shaft, Ducktown, Tenn., 37 feet below water level. R. C. Wells, analyst. EMMONS and LANEY: *Idem.*

5. Capote mine, Cananea, Mex., 300-foot level. G. W. Hawley (chief chemist Cananea Consolidated Copper Company), analyst.

Influence of Primary Ores on the Extent of the Secondary Sulphide Zones.—The vertical extent of the secondary sulphide

zone depends partly on the amount of fracturing of the primary ore body and the size, continuity, and character of the fractures. The fractures determine the course of descending waters and the rates at which the solutions descend. In their descent the metal-bearing solutions react on the walls of the watercourses, and these reactions result in the deposition of certain metals. These changes depend not only on the rate at which the solutions de-

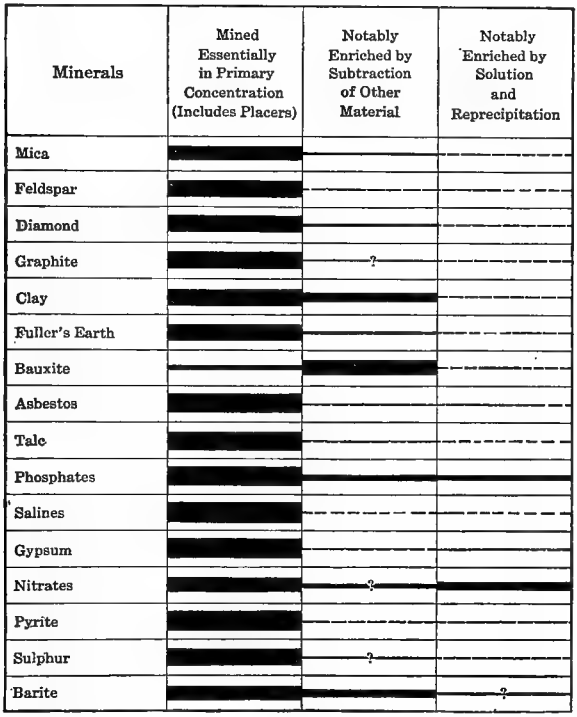


FIG. 160.—Diagram showing approximately by width of line an estimate of the relative importance of enrichment of certain non-metallic minerals. Broken lines indicate few or no deposits of value. Graphite, asbestos and talc which are developed in part by regional metamorphism are placed with the minerals mined in primary concentrations.

scend but also on the chemical environment through which they pass. In limestone or in calcite or siderite gangue the downward migration of copper would be delayed, at least temporarily, by the formation of carbonates, and calcite would quickly drive gold from acid solutions in which it was held dissolved as chloride.

Dilute acid waters dissolve pyrrhotite rapidly and set free hydrogen sulphide. Under similar conditions the zones of

secondary ores formed from primary ores that carry abundant pyrrhotite, though generally richer, are of smaller vertical extent than those of secondary ores formed from primary ores of pyrite and chalcopyrite that contain no pyrrhotite, for the reaction is brought near to completion more quickly. Briefly stated, the vertical extent of the secondary sulphide zones[1] varies inversely with the rate at which the descending sulphate solutions attack the

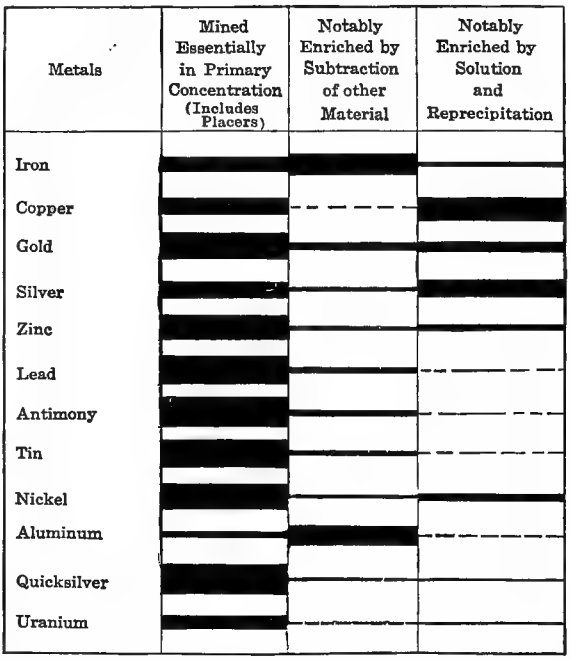


FIG. 161.—Diagram showing approximately, by width of line, an estimate of the relative importance of superficial enrichment in ore deposits and protores of several metals. Placers and all other deposits formed at places where no ore body or protore was present before are grouped in the first column with primary deposits. Broken line indicates fewer or smaller deposits than solid line; short dashes indicate fewer or smaller deposits than line with long dashes.

ore and gangue minerals through which they pass. In superficial alteration each metal behaves differently, its action depending on its chemical relations. These are discussed in sections treating separately the deposits of the metals. A summary showing the relative importance of superficial enrichment for several non-metals is shown by Fig. 160, and for metals by Fig. 161.

[1] EMMONS, W. H.: The Enrichment of Ore Deposits. U. S. Geol. Survey *Bull.* 625, pp. 152–154, 1917.

CHAPTER VIII

STRUCTURAL FEATURES OF OPENINGS IN ROCKS AND EPIGENETIC MINERAL DEPOSITS

OPENINGS IN ROCKS

With respect to size openings are placed in three groups—supercapillary, capillary, and subcapillary. Supercapillary openings are those in tubes that are more than 0.508 millimeters in diameter, or sheet openings more than 0.254 millimeters wide. In them water obeys the ordinary laws of hydrostatics.

Capillary openings are tubes with holes less than 0.508 and greater than 0.0002 millimeter in diameter, or sheet openings between 0.254 and 0.0001 millimeter wide. In these water does not obey the ordinary laws of hydrostatics but is affected by capillary attraction. Water will not circulate so freely in such openings because of the greater friction along the walls. Hot water may move through such openings more readily than cold, however, and, under pressure, either hot or cold solutions may be forced through capillary openings.

Subcapillary openings include tubes with holes less than 0.0002 millimeter diameter and sheet openings less than 0.0001 millimeter wide.[1] In these the attraction of the molecules of the solid extends across the open space. Water may enter such openings, but it tends to remain as if fixed to the walls prohibiting further entrance of solutions. Circulation of solutions at ordinary temperatures through such openings is therefore very slow.

If two rocks have equal amounts of pore space—supercapillary in one and subcapillary in the other—the one with the larger openings will afford more favorable conditions for the movement of solutions. Muds, clays, shales, and rock powders, which contain exceedingly minute openings, are the great natural barriers to circulating waters, whether the waters are hot or cold. In the following genetic classification of openings the supercapillary

[1] DANIEL, ALFRED: "A Textbook of the Principles of Physics," p. 315, 1895.

VAN HISE, C. R.: A Treatise on Metamorphism. U. S. Geol. Survey *Mon.* 47, p. 135, 1904.

openings and the larger capillary openings are considered chiefly, for most epigenetic deposits are related to such openings. It is noteworthy, however, that rocks containing subcapillary openings may be replaced by solutions that are under sufficient pressure at high temperature; but under most conditions such rocks tend to impede the circulation and thus to limit the size of ore bodies. Solutions that deposit ore in the minute openings in rocks generally move outward from the larger openings or master fractures.

With respect to their origin, openings in rocks are classified as follows:

PRIMARY OPENINGS:
- Intergranular spaces.
- Bedding planes.
- Vesicular spaces.
- Openings in pumice.
- Miarolitic cavities.
- Submicroscopic spaces.

SECONDARY OPENINGS:
- Formed by solution:
  - Caves.
  - Geodes.
  - Solution cavities in veins, etc.
- Formed by movement:
  - Shrinkage cracks due to dehydration, cooling, loss of fluids, etc.
  - Openings due to force of crystallization.
  - Openings due to the thrust of solutions.
  - Openings due to the greater earth stresses.

PRIMARY OPENINGS

The pore spaces in sedimentary rocks constitute a percentage of the volume of the rock ranging from less than 1 up to 20 or even more. The size of the grains does not determine the amount of pore space; a fine-grained rock may be as porous as a coarse conglomerate.[1] Figure 162 represents a section of several balls piled so as to represent rounded sand grains. It is obvious that if this figure were to be increased or decreased in size the changes would affect similarly the solid balls and the spaces between

[1] SLICHTER, C. S.: Theoretical Investigation of the Motion of Ground Waters. U. S. Geol. Survey *Nineteenth Ann. Rept.*, part 2, p. 305, 1899.

KING, F. H.: Principles and Conditions of the Movements of Ground Water. U. S. Geol. Survey *Nineteenth Ann. Rept.*, part 2, p. 135, 1899.

them. The amount of space depends principally upon the assortment of grains and the system of packing. If small grains fill in the spaces between large grains, the porosity is obviously diminished.

The pore spaces of the more coarsely granular rocks like sandstone are more likely to serve as seats of ore deposition than those in fine-grained rocks like shales. Colloidal matter in shale also tends to decrease its permeability.

Magmas generally contain included fluids. When the magmas are erupted and flow out upon the surface, pressure is relieved and the fluids expand and escape as gases. If they expand when

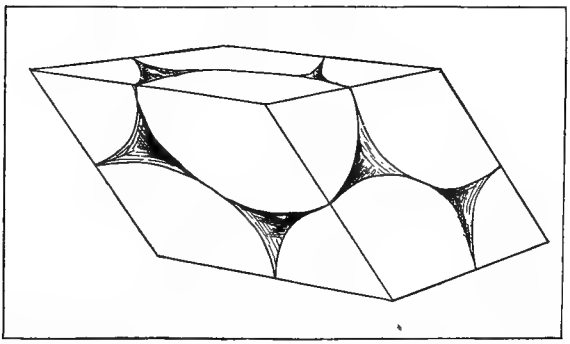


FIG. 162.—Section of balls with triangular pore spaces. (*After Slichter, U. S. Geol. Survey.*)

the lavas are in a sticky or viscous condition, and near the point of solidification, the openings due to expansion are preserved. In the diabases of the Keweenaw region of Michigan (see page 429) such openings contain ore and gangue minerals in large quantities.

Bedding planes are due to the assortment or sizing of material during transportation and deposition. On account of the assortment of grains there may be also different arrangements of the pore spaces in the different beds. Consequently, even in a nearly homogeneous rock the different beds commonly have different degrees of permeability. Water moving along the beds may follow the most permeable layer, but water moving across them must traverse also the most impermeable layers. Solutions will therefore pass along beds more readily than across them. Because of the greater permeability of certain layers, many ore deposits that obviously have been introduced after the

beds containing them were laid down are found below beds of shale or beds of material somewhat more impermeable than the associated beds. Deposition may take place along bedding planes also because certain layers are more readily replaced than others. Bedding planes, especially in tilted rocks, are likely to be fissured and faulted because they are planes of easy separation.

Openings in pumice and miarolitic cavities are not important as seats of deposition, although miarolitic cavities in pegmatites commonly contain gem minerals, such as beryl, tourmaline, and topaz.

The denser rocks, which appear solid, contain nevertheless small amounts of pore space. A granite, which under the microscope has no visible openings, will absorb a small amount of water in the cold. At high temperatures the speed of absorption is increased, and under pressure hot water may be forced through the denser rocks.

SECONDARY OPENINGS

Openings Formed by Solution.—In soluble rocks like limestones and dolomites large openings may be formed by solution and by removal of rock matter.[1] As a rule solution is more active above the water level, but large cavities have been found considerably below the present water level, especially where subsequent to solution there have been changes in the drainage or climate and in the position of the water level.

Before the development of the theory of replacement large solution cavities, such as limestone caves, were assumed to play an important part in the genesis of many ore deposits, but most investigators at present are inclined to minimize their importance.

Openings Due to Shrinkage.—Shrinkage may be caused by dolomitization, dehydration, cooling, and other processes. If a fairly pure limestone is changed to dolomite without addition of carbon dioxide a shrinkage of about 12 per cent. takes place. The porosity of some dolomites is assumed to be due to shrinkage.

[1] Siebenthal, C. E.: Origin of the Zinc and Lead Deposits of the Joplin Region. U. S. Geol. Survey *Bull.* 606, p. 28, 1915.

Smith, W. S. T., and Siebenthal, C. E.: U. S. Geol. Survey *Geol. Atlas*, Joplin district folio No. 148, p. 11, 1907.

Bain, H. F., and Van Hise, C. R.: Preliminary Report on the Lead and Zinc Deposits of the Ozark Region. U. S. Geol. Survey *Twenty-second Ann. Rept.*, part 2, pp. 23–228, 1901.

Cracks due to shrinkage in drying are common. Cooling cracks are formed soon after the solidification of igneous rocks, before they have cooled to the temperature of the surrounding rocks.

Openings Due to the Force of Crystallization.—The force which crystallizing matter exerts on the containing walls has been assumed to be sufficient to push the walls apart. If this force so operates it would be supposed that a metalliferous solution, having once gained entrance to a fissure, however narrow, could enlarge the fissure while it was being filled. This process probably operates to some extent, but its effects in general appear to be of limited application.

Openings Due to Pressure of Solutions.—In his discussion of the origin of certain small lenticular bodies of quartz ore in the schists of the southern Appalachians, Graton[1] has suggested that the metalliferous solutions themselves were under heavy pressure, sufficient to push the rocks apart along their cleavage planes, making the openings while they filled them, after the manner of igneous injections.

Openings Due to the Greater Stresses.—The earth is losing heat and shrinking. The exterior or shell receives heat from the interior and radiates it but probably remains at approximately the same average temperature through long periods. The loss of heat causes the interior to shrink more rapidly than the shell, which is then too large to fit the core. The shell is not strong enough to bear its own weight. Consequently it is a failing structure which is pulled downward by gravity and is wrinkled here and there, thus becoming smaller. There are probably also causes other than the loss of heat for the shrinkage of the interior.[2]

As a result of this failure of the shell, rocks are folded and mountain chains are formed. These are commonly ascribed to compressive stresses, because they are formed in the main by compression and shortening of the earth's crust.

When magmas are thrust into the crust or extravasated upon the earth, the rocks above the places they previously occupied tend to settle, and such readjustment sets up stresses of various kinds. Relief of stress may be accomplished by fracturing.

The larger earth fractures are commonly referred to three

[1] GRATON, L. C.: Reconnaissance of Some Gold and Tin Deposits of the Southern Appalachians. U. S. Geol. Survey *Bull.* 293, p. 60, 1906.

[2] CHAMBERLIN, T. C., and SALISBURY, R. D.: "Geology," vol. 1, p. 548, 1909.

classes—compressional fractures, tensional fractures, and torsional fractures.

Compressional Fractures.—Many fractures filled with ore have been formed by the relief of compressive stresses. In the classic experiment of Daubrée[1] a brittle block was subjected to pressure applied at its end. The block when viewed from the side shows two sets of fissures approximately at right angles to each other, making angles of about 45° with the direction of pressure (see Fig. 163). In some mining districts there are two groups of nearly parallel intersecting fissures, and from analogy with Daubrée's experiment these are assumed to have resulted from compressive stresses.

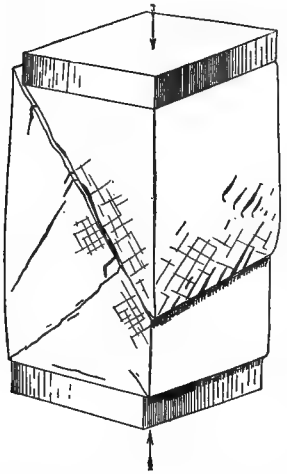


FIG. 163.—Block of material deformed by pressure applied at end. (*After Daubrée.*)

In this experiment it was possible for movement outward to take place in all directions except vertically. Consequently several coördinate systems of fractures are shown on the four free sides. But if the block had been buttressed on one, two, or three sides, then movement would have been restricted and there would be a smaller number of systems.

Tensional Fractures.—Rupture by tension in homogeneous bodies takes place in planes that lie approximately at right angles to the direction of the force. Of the greater stresses acting parallel to the earth's surface, the dominant ones are compressional rather than tensional, and the larger number of ore veins are probably related to the fractures resulting from compression. Some fissures, however, are clearly due to tension that results from compressional stress. Thus when brittle rocks are compressed into folds, fractures may be formed across the bedding, especially near the axes of the folds. The crest of an anticline may be stretched as a result of compression of its limbs. At the crests of folds rocks may separate also along the beds,

[1] DAUBRÉE, A.: "Études synthétiques de géologie expérimentale," p. 318, 1879.

BECKER, G. F.: Finite Homogeneous Strain, Flow, and Rupture of Rocks. Geol. Soc. America *Bull.*, vol. 4, p. 13, 1892.

leaving open spaces which may be filled with ore. Some bedding-plane deposits are either confined to or greatly enlarged at the crests of anticlines.

Torsional Fractures.—To illustrate the effect of torsion, experiments have been made[1] in which a plate of glass covered with a brittle wax was held firmly at one end and twisted. Figure 164 shows the character of the fractures resulting from such stresses. They follow two general directions, cross at nearly the same angles, and are inclined about 45° to the axis of torsion. Some cracks are very short; others extend across the plate.

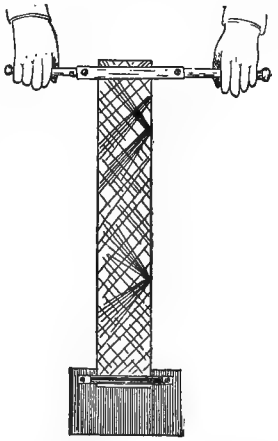


FIG. 164.—Sketch showing effect of torsion on glass plate. Lower end was held fast to block and upper end was twisted. (*After Daubrée*).

Becker, Leith[2] and Lindgren[3] regard torsional cracks as due to tension rather than compression. In general torsional cracks are not considered important seats of ore deposition. In some districts, however, the master fractures are joined at small angles by many branching fractures. Possibly torsional stresses have modified some vein patterns formed principally by compressional stresses.

OPENINGS IN ROCKS AND EPIGENETIC DEPOSITS

Fissure.—A fissure is an opening or parting that is due to movement. It may be a mere crack with no visible space, like a crack in a pane of glass that does not extend across it, or it may present a wide open space.

If there has been movement parallel to the plane of the fissure it is termed a fault fissure. Joints are essentially small fissures.

Fissures range in length from inches to miles. Some faults have been traced for many miles, and some fault systems for

[1] DAUBRÉE, A.: Études synthétiques de géologie expérimentale," p. 310, 1879.

BECKER, G. F.: The Torsional Theory of Joints. Am. Inst. Min. Eng. *Trans.*, vol. 24, p. 130, 1894. Finite Homogeneous Strain, Flow, and Rupture of Rocks. Geol. Soc. America *Bull.*, vol. 4, p. 48, 1893.

[2] LEITH, C. K.: "Structural Geology," p. 15, 1913.

[3] LINDGREN, WALDEMAR: "Mineral Deposits," p. 135, 1913.

scores or hundreds of miles; but few single mineralized fissures are known to be more than 5 or 6 miles long.

Many fissure veins have been explored to depths of half a mile or more, and there is much evidence that some of them when formed extended more than a mile below the surface.

Many fissures are narrow. There is evidence that many veins have been formed mainly by replacement; the original spaces along the fissures of such deposits were narrower than the veins, and perhaps some were only thin openings. Movements along a narrow undulating fissure may yield large open spaces (Fig. 165).

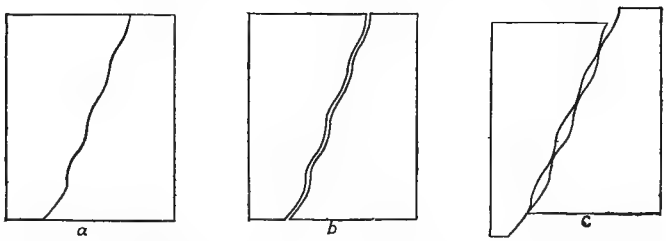


FIG. 165.—*a*, Undulating fissure; *b*, undulating fissure after movement at right angles to its plane; *c*, indulating fissure showing lenticular openings developed by movement along plane.

Vein.—A vein[1] is a tabular mineral mass occupying or closely associated with a fracture or set of fractures formed by deposition from solutions either by filling fissures and pores in the wall rock, or by replacement of the wall rock, or by both filling and replacement. The term "true fissure vein," as generally used, is intended to imply persistence in depth. A fault-fissure vein is a vein that occupies a fault fissure.

Lode.—A lode is a tabular ore body, an ore body with one short and two long dimensions. The term may be applied to veins, deposits in sheeted or fracture zones, or replaced beds. It is applied also to deposits filling a number of thin, closely spaced, anastomosing fissures.

Reef.—In Australia and some other British colonies the term "reef" is used synonymously with "vein." In general it is applied to a vein that projects above the surface, but in Australia it is applied to some ore bodies that do not outcrop. The "saddle reef" is a deposit at the crest of an anticline.

[1] LINDGREN, WALDEMAR: Metasomatic Processes in Fissure Veins. Am. Inst. Min. Eng. *Trans.*, vol. 30, p. 580, 1901.

Ledge.—The term "ledge" is sometimes used as a synonym of "vein." Like "reef," it may designate a lode projecting above the surface. As defined by Ransome,[1] it is applied to irregular masses of altered and mineralized rock, traversed by multitudes of small, irregularly intersecting fractures that pass locally into areas of thorough brecciation.

Ladder Vein.—A ladder vein is a fractured zone in which there are cross fractures more or less regularly spaced. The type is not common and generally is found in dikes or earlier veins that are fractured.

Fractured Zone.—A fractured zone is a mass of rock cut by a large number of small irregular fractures, the mass as a whole being more or less tabular (see Fig. 166). The fissures ordi-

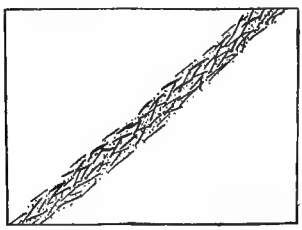


FIG. 166.—Fractured zone.

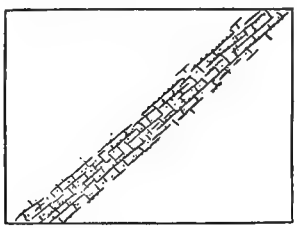


FIG. 167.—Reticulated vein.

narily are filled with veinlets very closely spaced, and the country rock is replaced with ore.

Reticulated Vein.—A reticulated vein (Fig. 167) is a fractured zone in which the fissures are rudely coördinate, forming a net-like pattern.

Disseminated Deposit.—In some ore bodies the metallic minerals occur as thin, closely spaced seams or veinlets, and the rock between carries also numerous "shots" and seams of ore, the whole mass being workable where mining and milling costs are sufficiently low. These are commonly termed disseminated deposits (Fig. 168).

Breccia Vein.—In a breccia vein the vein matter fills spaces around numerous fragments of wall rock inclosed within the walls of the fissure (Fig. 169).

Stockwork.—A stockwork is a mass of rock cut by a large number of intersecting reticulated or irregular veins or veinlets.

[1] RANSOME, F. L.: The Geology and Ore Deposits of Goldfield, Nevada. U. S. Geol. Survey *Prof. Paper* 66, p. 150, 1909.

The country rock is generally impregnated with or replaced by "shots" of ore, so that the whole deposit may be workable. The stockwork differs from the reticulated vein or fractured zone in that the mass as a whole is generally less definitely tabular. The ore in a stockwork is usually disseminated ore.

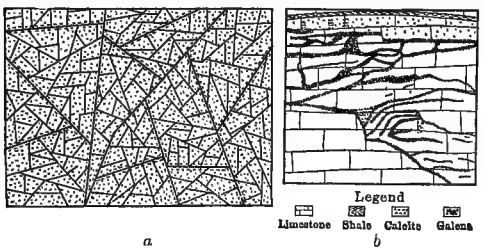


FIG. 168.—*a*, Disseminated deposit in igneous rock; *b*, disseminated deposit in limestone. (*After Buckley.*)

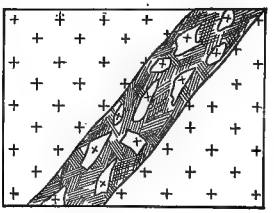


FIG. 169.—Breccia vein.

Sheeted Zone.—A sheeted zone (Fig. 170) is made up of a number of closely spaced parallel fissures. These may be filled with ore, and the country rock between them may be partly replaced.

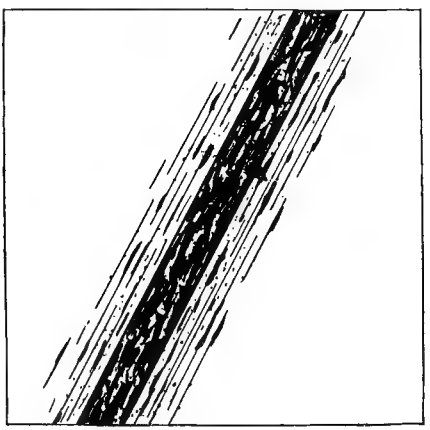


FIG. 170.—Sheeted zone.

Shear Zone.—A shear zone (Fig. 171) is a zone of crushed rock formed by compressive stresses, in which the openings or slips are generally small, tabular, and closely spaced. The individual fissures may be smaller than those of sheeted zones, and in general there is clearer evidence of compression.

Gash Vein.—Gash veins[1] occupy fissures of moderate extent, usually restricted to one formation and not connected with any very profound earth movement. In southwestern Wisconsin, where they are typically developed, they occupy joint cracks.

Run.—A ribbon-like, irregular ore body, lying flat or nearly flat, following the stratification, is called a run. Many are formed at the intersections of ore horizons with vertical fissures.

Flats and Pitches.—Flats follow nearly horizontal bedding planes, and pitches follow dipping joint planes (see pages 464–466). These deposits, which occupy openings formed by the settling of limestone over a shrinking bed, are structurally unique. They have been found only in southwestern Wisconsin.

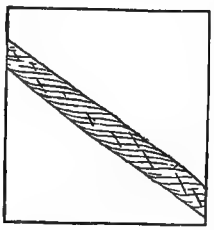


FIG. 171.—Shear zone.

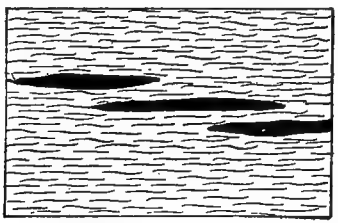


FIG. 172.—Overlapping lenses.

Lens.—A lens is a rudely tabular body that thins out at the edges. Most tabular bodies, as they have not infinite extent, are strictly lenses, but the term is commonly used to define a relatively small body inclosed in schist and lying parallel to the schistosity. Overlapping lenses are shown in Fig. 172.

Pod.—A pod is a rudely cylindrical ore body that decreases at the ends like a cigar. The term was formerly used to describe certain bodies long in one and short in two dimensions, inclosed in schist, the long axis lying parallel to the schistosity. It is not much used at present.

Fahlband.—The term "fahlband" was first applied to belts in which disseminated deposits of pyrite, pyrrhotite, and chalcopyrite appear in dark micaceous schists. The original fahlbands at Kongsberg, Norway, are more than 100 feet wide. They are themselves of too low grade to work, but the silver veins near them are enriched. When the sulphides weather and dark minerals turn rusty brown, the bands become of lighter color, hence the name (gray band).

[1] WHITNEY, J. D.: "Metallic Wealth of the United States," p. 48, 1854.

Influence of Rock Structure on Fissuring.—In some districts fissures show a strong tendency to follow bedding planes, planes of schistosity, contact planes, dikes, and other structural features. This tendency is more noticeable where such planes are regular and strongly developed. They are generally planes of weakness and therefore favor rupture. They do not localize a rupture completely, however, except where they are favorably oriented with respect to the forces that are applied. Generally

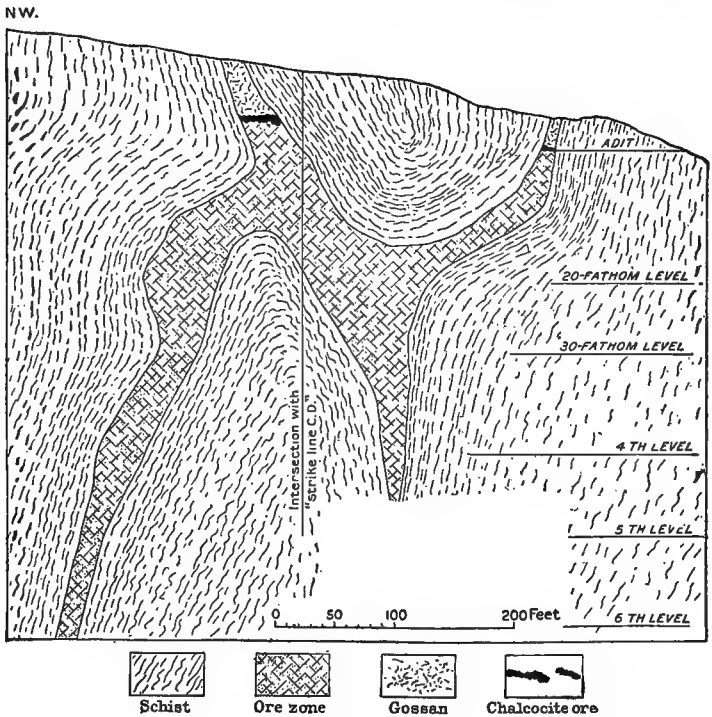


FIG. 173.—Vertical section of Mary mine, Ducktown, Tenn.

the fissures follow such planes at some places and cut across them at others. They may follow a regular contact along both strike and dip, or only along the strike. Many bedding-plane deposits are simply veins which follow bedding-plane fissures. A sheeted zone, consisting of closely spaced parallel fissures, may be formed where highly schistose and somewhat brittle rocks are fractured by compressive stresses. Many igneous dikes localize fracturing and ore deposition because they are more brittle than associated

rocks. Planes of contact between two rock formations in many districts are likewise planes of rupture.

Many valuable veins become thin or "fray out" in passing from one formation to another. Many epigenetic deposits follow bedding planes because a certain bed is chemically more hospitable to deposition or because it is more readily fractured than associated beds. In some places a long, slender deposit is formed at the intersection of two fissures or at the intersection of a fissure and a dike or of a dike and a favorable bed. Such deposits, if vertical or highly inclined, are known as "chimneys;" if approximately flat they are commonly called "ribbons."

Chambers or chambered deposits are irregular or almost equidimensional. Generally they are formed at places of maximum fracturing of the containing rock.

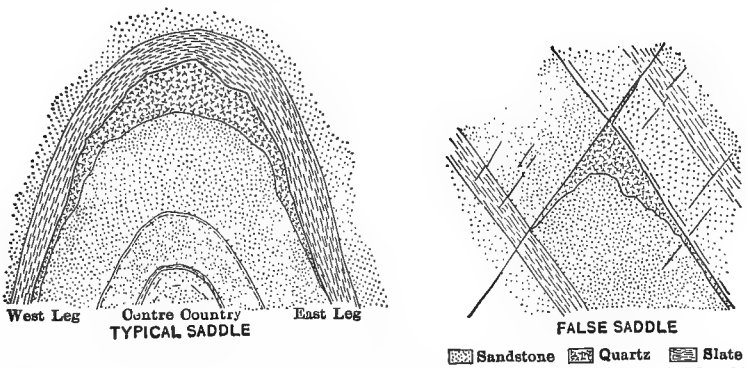


FIG. 174.—Sketch showing typical saddle and "false saddle." (*After Rickard.*)

Anticlinal Deposits; Saddle Reefs.—In many districts of folded rocks ore deposits are concentrated on the axes of folds, especially at the crests of anticlines (Figs. 173, 174). Five possible modes of origin for such deposits should be considered.

1. The folding of ore bodies after their deposition may be attended by thickening at the crests of folds and thinning along their limbs.

2. Thin beds of limestone or other rocks compressed into folds and thickened at crests of anticlines may have been replaced by mineral-bearing solutions.

3. Mineral matter may be introduced into openings at axes of folds where brittle beds have been fractured, or where beds have been separated by movement.

4. Segregation of mineral matter in folds may be accomplished by solutions during dynamic or regional metamorphism.

5. In igneous and in sedimentary rocks fissures that have approximately parallel strikes and that cross and dip in opposite directions may be more heavily mineralized at and near the lines of their intersections.

Synclinal Deposits; Inverted Saddles; Troughs.—In some mining districts the ores are concentrated in synclines or structural troughs. Synclinal deposits may be formed by several groups of processes corresponding to those mentioned above in the discussion of the origin of anticlinal deposits. They may be formed by the replacement of limestone beds at synclines, by the filling of openings between two beds at synclines, or by replacement in zones of fracturing on synclines. During dynamic metamorphism tabular deposits may be folded to form synclines. In areas of closely folded rocks openings due to fracturing are probably less commonly developed along synclinal axes or planes than along anticlinal planes because in a folded series of beds any given zone that is favorable for the deposition of ore will lie at lower altitudes in synclines than in anticlines, and in a syncline the favorable zone is likely to be covered by a greater and therefore heavier mass of overlying beds. Ores formed along anticlines or along synclines are characteristically developed in the deep vein zone or at moderate depths. Ore folds are comparatively rare in deposits formed by ascending thermal waters at shallow depths. "False saddles" or "false inverted saddles," both of which are formed near lines of junction and along intersecting fractures, may be formed at all depths.

Fracture Systems.—Types of fracture systems that are commonly recognized are parallel systems, conjugated systems, radial systems, and irregular patterns.

Parallel systems of fractures are developed in many districts. The veins of such systems have approximately the same strike and the same direction of dip. Some such systems are developed by compressive stresses. In many districts the principal veins are parallel, but many subordinate veins join or cross them. Systems of rudely parallel veins are found at Butte and Philipsburg, Montana, in the Wood River district, Idaho, and at many other places.

A conjugated system is one in which the veins are approximately parallel in strike but dip in opposite directions, or in which the veins in place form two parallel groups. Commonly they strike approximately at right angles to each other. Con-

jugated systems are developed in the Nevada City and Grass Valley regions, California, in Cornwall, England, and at Freiburg, Saxony.

In some vein systems there are major fractures from which numerous minor fractures extend. The minor fractures commonly make angles of 30° to 60° with the major fractures and are rudely parallel to one another. Where they are closely spaced, large bodies of ore may be formed along them. At Butte, Montana, in the Leonard mine, such deposits are extensively developed. The result of such transverse fissuring Sales has designated "horsetail structure."[1]

Radial patterns of ore veins are not common, though radial systems of dikes are known in many districts. They are represented in some degree of perfection at Cripple Creek, Colorado, where the principal fissures are confined to an area but little larger than the volcanic neck in and around which the lodes are grouped. Basic dikes are arranged radially about the volcanic center, and many of the veins follow the dikes.

Irregular Patterns.—Irregular patterns of ore veins are not uncommon. In these the veins occupy fissures that can not be referred to systems.

[1] SALES, RENO: Ore Deposits of Butte, Montana. Am. Inst. Min. Eng. *Trans.*, vol. 46, pp. 13, 17 (see particularly Fig. 2), 1913.

CHAPTER IX

METASOMATIC PROCESSES, MINERAL ASSOCIATIONS, AND METALLOGENIC PROVINCES

Metasomatic Replacement.—Metasomatism is a chemical process by which a mineral or rock is replaced by another of different composition in such a manner that the form of the earlier body is preserved. Replacement goes on under widely varying conditions and operates in the formation of epigenetic ores of every class. Metasomatism is important in rock weathering, oxidation, and secondary sulphide deposition.

Metasomatism takes place by solution and reprecipitation in very small openings. If large solution cavities form before appreciable precipitation begins, minute textures will not be preserved, and the material undergoing alteration may collapse, so that even its form will be destroyed; but if precipitation of the new substance begins before the old substance is completely dissolved the form or texture of the old substance may be preserved. This frequently happens where the rock subjected to attack contains a radicle that unites with one present in the solution, to form an insoluble compound. In many places the zone of solution and reprecipitation is so narrow that no space between the old and new substance is seen even on close examination. In the zone of oxidation the secondary substances, such as carbonates and oxides, usually contain numerous cavities; their porous or spongy character, even in minute particles, is generally evident. At some places, where a new mineral has replaced an old one metasomatically, a thin zone occupied by a spongy mass is evident between the old and new substances. Locally, however, dense new crystals and crystalline bodies may form in the open-textured mass, which later may become completely indurated by subsequent deposition of like material.

In metasomatic replacement reprecipitation generally succeeds solution so closely that they seem to be essentially parts of a single process.

As a rule there is no great increase of volume during metasomatism. Much increase of volume by swelling would result in the destruction of any structural features present. Generally

hydrothermal metamorphism results in some decrease of volume; the rocks after alteration are commonly porous. That is the case also when metasomatic alteration takes place during weathering.

Rocks replaced during contact metamorphism are generally dense and impervious. There is, nevertheless, no evidence of much change of volume during contact metamorphism (garnetization), and there is much evidence to the contrary.[1]

A replacement deposit[2] is one formed by metasomatism. Replacement veins are veins along which the wall rocks are replaced by vein matter (Figs. 175, 176). Where veins are formed by hot waters, the country rock along the vein fissures is generally altered, but it is not always replaced by ore. Some of the sub-

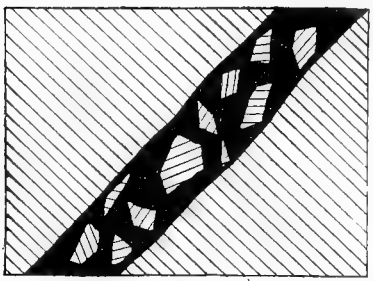


FIG. 175.—Vein filling a fissure, showing inclosed fragments whose structure is oriented unlike similar structure in wall rock.

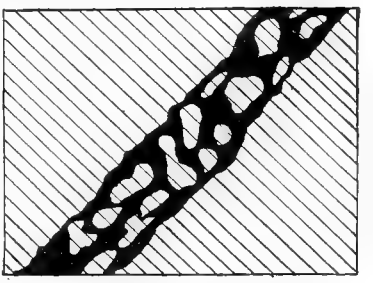


FIG. 176.—Vein formed by replacement, showing inclosed fragments whose structure is oriented like similar structure in wall rock.

stances in the solutions penetrate the wall rock and some remain in the open spaces. The metalliferous solutions may not penetrate the wall rock in noteworthy amounts or convert it to ore; the wall rock may be changed so little that its contacts with the fissure filling are sharp.

Pseudomorphs.—A pseudomorph is a mineral or group of minerals having the crystal form of another mineral of different composition. Pseudomorphs are developed by metasomatism. The term "pseudomorph" has been expanded to include forms other than those of minerals. Remains of plants or animals or

[1] This is particularly well shown in the deposits of the Mackay region, Idaho, described by J. B. UMPLEBY. U. S. Geol. Survey *Prof. Paper* 97, pp. 70–71, 1917.

[2] LINDGREN, WALDEMAR: Metasomatic Processes in Fissure Veins. Am. Inst. Min. Eng. *Trans.*, vol. 30, pp. 578–692, 1900. The Nature of Replacement. *Econ. Geol.*, vol. 7, pp. 521–535, 1912.

any bodies of characteristic shape become pseudomorphs after alteration of the material if the original shape is preserved. In many replacement deposits the larger crystals of the original rock are replaced by many smaller crystals, and the new crystals are grouped within the outlines of the older crystals so that the outlines are clearly shown. The larger features of an older rock, such as jointing or sheeting, may be preserved in the rock that replaces it. In replaced sedimentary rocks bedding may be preserved. In some bodies replacement has been complete, even the last evidence of the original rock texture being destroyed. In many places, however, there is between the massive vein material and the country rock a less intensely altered zone in which the texture of the original rock is preserved. Pseudomorphism (Fig. 177), or the preservation of ancient structure,

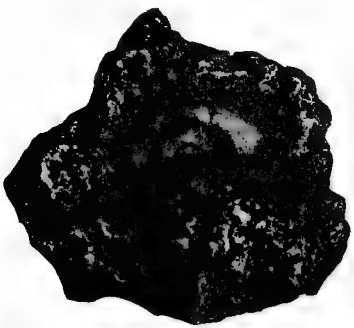


FIG. 177.—Fossil shell replaced by native silver. (*After Spurr, U. S. Geol. Survey.*)

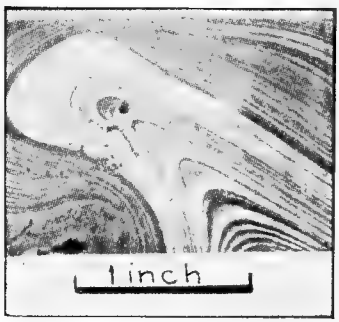


FIG. 178.—Photograph showing limonite banding developed in felsite by oxidation. The felsite contains pyrite which oxidizes to limonite. (*After Bastin and Laney, U. S. Geol. Survey.*)

is in itself evidence that the volumes of old material are essentially unchanged. Much shrinkage or expansion would alter or destroy the structure or render it indistinct.

Banding and Crustification.—Some replacement deposits show banding, especially where the replaced rocks were banded shales or impure limestones. Banding[1] is not unknown also in normal limestone that is replaced, although it is less common. Homogeneous igneous rocks that are hydrothermally altered also may show banding. Banding is developed also during weathering

[1] LINDGREN, WALDEMAR: Processes of Mineralization and Enrichment in the Tintic Mining District. *Econ. Geol.*, vol. 10, p. 231, 1915.

LIESEGANG, R.: "Geologische Diffusionen," p. 83, 1913.

(Fig. 178). Deposits formed in open spaces are much more commonly banded than deposits that have replaced homogeneous rock. Symmetrical crustified banding is not developed by replacement.

Cavities.—Large cavities are rarely found in replacement deposits, except in the superficial zone. Veins that fill fissures very commonly contain many open spaces. Thus a crustified vein generally contains many elongated vugs, and these tend to be oriented in lines or with their longer axes approximately parallel to the plane of the vein. Such an arrangement of vugs is rare in deposits that replace the country rock.

Crystal Boundaries.—Minerals that fill fissures commonly form imperfect crystals, the ends that are attached to the walls being poorly developed.[1] Crystals of certain minerals that have been deposited by replacement of the wall rock may have sharp boundaries, all sides being completely shown. Some species are commonly developed in great perfection. In the following list of minerals[2] that are often formed by replacement those named first are more likely to be developed with good crystal outlines: Rutile, tourmaline, arsenopyrite, pyrite, magnetite, barite, fluorite, epidote, pyroxene, hornblende, siderite, dolomite, albite, mica, galena, sphalerite, calcite, quartz, orthoclase. Some other minerals, like chalcopyrite, sericite and some chlorites very rarely show crystal outlines, even under the microscope.

Boundaries of Deposits.—Replacement deposits are more irregular in outline than veins filling fissures (Figs. 175, 176). Veins may narrow to thin sheets or swell to broad masses, but normally the changes are gradual. A replacement deposit, on the other hand, may become very thin at one place and swell abruptly at another, so that the entire deposit may be a chain of large ore bodies connected by thin seams of ore, rather than a tabular and nearly uniform mass. Some replacement deposits, however, are fairly uniform in width.

Contacts.—Replacement deposits generally grade into the country rock. In some deposits the change from ore to country rock is so gradual that the boundary of the ore body can be determined only by assays. On the other hand, in some replacement deposits the ore may grade into country rock through a zone

[1] IRVING, J. D.: Replacement Ore Bodies and the Criteria for their Recognition. *Econ. Geol.*, vol. 6, pp. 527–561, 619–663, 1911.

[2] LINDGREN, WALDEMAR: "Mineral Deposits," p. 158, 1913.

less than 1 inch wide, and in limestone the contact between mineralized and unmineralized rock may be abrupt.

Fragments.—Small irregular fragments included in fissure fillings ordinarily have sharp outlines. They are generally altered somewhat by the vein-forming solutions, but as a rule their original shape is still clearly shown. On the other hand, fragments included in replacement deposits may be rounded somewhat by solution, especially on their edges that are most exposed. Veins in siliceous sedimentary rocks and in igneous rocks more commonly contain fragments of the wall rock with sharp boundaries than veins in limestone.

Orientation of Fragments.—Near the border of a replacement deposit the rock that has been replaced may have distinctive features of structure such as bedding planes or parallel planes of schistosity. Fragments included in the replacement deposit may have similar features. If these are similarly oriented and oriented like the corresponding features in the country rock, it is a natural inference that the material surrounding them was formed by replacement (see Fig. 176), for some of them would probably have been rotated had they been broken from the parent mass by movement (see Fig. 175).

Where a replacement vein in sedimentary rock cuts across several beds of different composition, there is generally selective replacement. Siliceous or shaly beds may be only slightly changed, whereas the calcareous members may be extensively replaced. The deposit may be wider in shale than in quartzite, and still wider in limestone than in shale.

Hydrothermal Metamorphism.—Hydrothermal metamorphism is the change that takes place through the agency of hot water acting on the wall rock in and near veins. The mineralizing solutions gradually soak into the rock, remove the more soluble parts, and replace them with new material. In some places the wall rock is only partly changed and may easily be recognized; in others it is completely removed, and new material takes its place. The process goes on gradually so that the texture and larger features of the rocks are often preserved. By comparison of the unaltered rock and the altered rock the nature of the changes becomes apparent. In igneous rocks calcium and sodium are generally removed and potassium is deposited. Silica, iron sulphide, and other sulphides or mixtures of them may replace the rock completely. Limestones and igneous rocks are

readily replaced; sandstone, quartzite, and clay rocks are in general less readily replaced, but along some veins these are changed also. As a rule the changes decrease outward from the vein, and the intense changes may disappear within 5 feet or less. Where the rocks are much shattered, however, they may extend 20 or even 100 feet or more away from the master fractures. Some minerals commonly developed by these changes are quartz, sericite (felty white mica), carbonates, chlorite, and orthoclase. The minerals produced depend upon the nature of the solutions that cause the changes and the depth at which they take place. The depth is important, because it influences temperature and pressure.

Certain types of alteration are common, among them "propylitization," which operates mainly to alter lavas and shallow intrusive rocks, particularly andesite, basalt, and rhyolite. Chlorite, pyrite, and often epidote are developed, with carbonates and sericite. If any glassy feldspars are present they become cloudy and dull, and the rock, owing to the development of chlorite, assumes a greenish cast. Many deposits formed in the zone of shallow veins are found in areas or propylitic rock.

At great depths the processes of hydrothermal alteration yield different products. The wall rocks of tin-bearing veins are commonly altered to greisen which is composed chiefly of coarse crystals of muscovite and quartz with one or all of the minerals: tourmaline, fluorite, and cassiterite. There are many other types of hydrothermal alteration, most of which are designated by the names of the principal mineral developed by the process.

Probably the most common type of alteration is sericitization, which takes place at moderate or intermediate depths. It is the characteristic type of alteration in the deposits of disseminated copper ore in porphyry. Sericitization is extensive at Morenci, Arizona and other copper camps of the southwest.

The following analyses and abridged notes from Lindgren's descriptions[1] show the changes that have taken place in the porphyry at Morenci as a result of hydrothermal processes. The normal quartz monzonite porphyry is a light-gray rock composed of orthoclase, plagioclase, quartz, and green biotite in a microcrystalline groundmass with much quartz and orthoclase. Some secondary minerals, such as sericite, epidote, chlorite, serpentine,

[1] LINDGREN, WALDEMAR: The Copper Deposits of the Clifton-Morenci District, Arizona. U. S. Geol. Survey *Prof. Paper* 43, p. 168, 1905.

ANALYSES OF FRESH AND ALTERED PORPHYRY FROM MINES AT MORENCI, ARIZ.

(W. F. Hillebrand, analyst)

	1	2	3	4	5
SiO_2	68.04	46.67	69.55	64.88	72.78
Al_2O_3	17.20	20.92	16.43	16.41	15.35
Fe_2O_3	0.34	0.37	0.46	0.65	0.55
FeO	0.67	0.36	0.11		0.10
MgO	1.05	0.85	0.62	1.12	0.89
CaO	2.21	0.15	0.15	0.11	0.14
Na_2O	5.33	0.16	0.17	0.12	0.36
K_2O	2.65	4.33	5.05	4.96	5.00
H_2O-	0.60	0.94	1.00	0.83	1.21
H_2O+	1.23	5.01	2.69	2.74	3.22
TiO_2	0.41	0.43	0.41	0.38	0.45
ZrO_2	0.01	Trace?	Trace	Trace	Trace
CO_2	None	None	None	None	None
P_2O_5	0.12	0.15	0.05	0.12	0.05
SO_3	.....	0.18	0.10	0.10	0.08
MnO	0.06	None	None	Trace?	None
BaO	0.10	0.04	0.05	0.07	0.02
SrO	0.03	None	None	Trace	None
Li_2O	Trace?	Trace	Trace?	Trace	Trace
F_2O_3	Trace				
FeS_2	0.24	19.18	3.09	4.96	0.06
Cu_2S	0.02	0.24	0.07	2.42	
Zn	.....	.....	.....	None	
ZnS	0.03	0.32			
Mo	None	.....	.....	None	
MoS_2	.....	0.20	None		
	100.34	100.50	100.00	99.87	100.26

1. Fresh monzonite porphyry. Ryerson mine, first level.

2. Altered monzonite porphyry. Ryerson mine, first level; drift on Humboldt vein at end of small crosscut in foot wall 40 feet east of Humboldt claim line.

3. Altered (silicified) porphyry. Ryerson mine, intermediate level, 550 feet west of West Yankie shaft.

4. Altered porphyry within chalcocite zone. Ryerson mine, lower adit level, Humboldt, from stopes 70 feet wide, 80 feet above level.

5. Altered porphyry from the surface.

and pyrite, are present in small amounts but do not greatly alter the composition of the rock, which is represented by analysis 1 in the accompanying table. Analysis 2 represents a specimen taken

MINERAL COMPOSITION OF FRESH AND ALTERED PORPHYRY FROM MINES AT MORENCI, ARIZ.

	1	2	3	4	5
Quartz	21.35	19.13	49.33	43.03	50.81
Orthoclase (mol.)	13.12				
Albite (mol.)	45.26				
Anorthite (mol.)	9.52				
Apatite	0.28	0.36	0.12	0.30	0.12
Zircon	0.02				
Magnetite	0.41				
Ilmenite	0.81				
Rutile	.....	0.43	0.41	0.38	0.45
Sericite	3.75	38.50	43.44	44.94	44.29
Kaolin	.....	17.90			
Chlorite	[a]3.04				
Serpentine	[b]0.98	[c]2.81	[d]1.71	[e]2.74	[f]2.71
Epidote	[g]0.59	.....	0.43	.....	[g]0.36
Alunite	.....	0.46(?)	0.26(?)	0.26(?)	0.21(?)
Water (below 100°C.)	0.60	0.94	1.00	0.83	1.21
FeS_2	0.24	19.18	3.09	4.96	0.06
Cu_2S	0.02	0.24	0.07	2.42	
SnS	0.03	0.32			
MoS_2	.....	0.20			
	100.02	100.47	99.86	99.86	100.22

[a] Amesite, MgO:FeO = 6:1.

[b] 0.39 per cent. MgO, 0.19 per cent. H_2O residue, with 0.40 per cent. SiO_2—too high in H_2O for serpentine.

[c] 0.84 per cent. MgO, 0.29 per cent. FeO, 0.53 per cent. H_2O residue, with 1.15 per cent. SiO_2—too high in H_2O for serpentine.

[d] 0.62 per cent. MgO, 0.39 per cent. H_2O residue, with 0.70 per cent. SiO_2 corresponds fairly well to deweylite.

[e] 1.11 per cent. MgO, 0.49 per cent. H_2O residue, with 1.12 SiO_2—too high in H_2O for serpentine.

[f] 0.89 per cent. MgO, 0.95 per cent. H_2O residue, with 0.87 per cent. SiO_2—too high in H_2O for serpentine.

[g] $Si\ Al_2O_3:Fe_2O_3$ = 4:1.

adjoining a 2-inch pyrite vein—a soft white chalky rock containing scattered pyrite and showing on a few seams a little chalcocite. The locality where this specimen was obtained is 600 feet below the surface and somewhat below the main chalcocite zone, although there is a little oxidation and chalcocitization of the vein. The rock is a felted mass of sericite with some granular

quartz and is cut by veinlets of kaolin. Pyrite is present in grains and crystals. Zinc blende, chalcopyrite, and molybdenite occur in small amounts as irregular grains and aggregates; also some rutile and zircon.

Sample 3, taken about 300 feet below the surface, is a hard white porphyry with small pyrite crystals. The original structure is almost lost, but under the microscope the outlines of feldspar crystals are visible. The rock consists chiefly of a very fine sericite felt with granular quartz; the quartz also occurs as veinlets with pyrite.

Sample 4, the disseminated chalcocite ore, is a soft white chalky rock, cut by many small seams of pyrite and chalcopyrite. In thin section the porphyry structure is retained, but the feldspars are entirely converted into sericite felt; the groundmass consists of granular quartz, filled with sericite. Pyrite occurs in crystals and anhedrons, largely in the altered feldspars but also with small masses of granular quartz.

Sample 5 is from the surface of the northeast spur of Copper Mountain, where the rock formed brownish-gray outcrops; the porphyry structure is still visible. A thin section shows it to be an entirely sericitized rock with pseudomorphs of feldspars and biotite. The groundmass consists mainly of fine-grained quartz, with sericite foils.

The mineral components of these rocks, calculated by L. C. Graton from analyses and thin sections, are shown in the table on page 280.

This table shows the altered rocks to consist chiefly of sericite, pyrite, quartz, and serpentine. Kaolin occurs only in sample 2, the only one taken immediately adjacent to an important seam or vein. The silica has not been materially changed, except in No. 2, where it is lowered to correspond to the high percentage of kaolin and pyrite. Alumina is generally constant but has been increased in No. 2; this increase is, however, probably due to conversion of sericite to kaolin, with attendant setting free of some chalcedonic or opaline silica. MgO, TiO_2, ZrO_2, and P_2O_5 remain nearly constant. Practically all CaO and Na_2O have been carried away and FeS_2 and K_2O have been added. The alteration indicates waters deficient in carbonates but rich in potash, iron, and silica.

Mineral Associations.—Veins may be separated in groups according to the ore and gangue minerals they contain and the

minerals that have been deposited in the wall rocks along the veins. These groups are not sharply set off from one another—indeed, the same vein may show considerable differences in composition at different places. Nevertheless, there are certain associations that are common: galena and argentite, galena and sphalerite, pyrite and gold, cinnabar and chalcedonic quartz, barite and fluorite, zeolites and native copper, calcite, adularia, and gold, and many others. Certain minerals are formed under certain conditions of temperature and pressure; thus the groups are outlined broadly by the depth of formation of the deposits. Even these greater groups of veins overlap, as is indicated by the table below. Some minerals persist through the entire range of vein formation. Thus quartz and pyrite are formed at all depths, and sericite is formed on the wall rock along veins of each of the major groups. Garnet, on the other hand, is found only in deposits of the deep zone, and alunite only in the shallow zone. In many veins the minerals formed by filling a fissure and those formed by replacement of the wall rock can not be sharply differentiated. Lists of minerals found in well-known mining districts are stated on subsequent pages.

Deposits Formed at Orifices of Hot Springs	Tufa.
	Sinter.
	Travertine.
Deposits of Shallow Zone	Baritic fluorite veins.
	Zeolitic native copper veins.
	Chalcedonic cinnabar veins.
	Alunitic kaolinic gold veins.
	Fluorite-tellurium-adularia veins.
	Gold-silver-adularia veins.
Deposits of Zone of Moderate Depth	Propylitic veins.
	Sericitic silver-gold veins.
	Sericitic copper veins and disseminated sericitic copper ores.
	Sericitic copper-silver veins.
	Sericitic zinc-silver veins.
Deposits of Deep Zone	Sideritic lead-silver veins.
	Sericitic calcitic gold veins.
	Tourmaline-gold veins.
	Tourmaline-copper veins.
	Cassiterite veins.
	Garnetiferous lead-silver veins.
	Garnetiferous silver-copper veins.
	Garnetiferous gold veins.

Metallogenic Provinces.—Petrologists have long used the term "petrographic province" for districts or regions that contain bodies of igneous rocks which, though differing somewhat in composition and character, nevertheless exhibit certain similar features that indicate similar genetic relations. Thus the batholithic intrusive rocks of western Montana are quartz monzonites; those of the Pacific coast are granodiorites; the rocks of the Cripple Creek region in Colorado are phonolites, syenites, etc., characterized by high percentages of alkalies. Similarly the ore deposits in some regions have certain characteristics that suggest nearly related genesis. Thus the zinc and lead deposits of southwestern Wisconsin, of eastern Tennessee, and of southwestern Missouri were all formed in Paleozoic limestones and are all remote from igneous rocks. Mineralogically these deposits are closely similar, and, though differing in structural relations, they may be placed in one group in the interior zinc-lead province. In eastern Ontario near Cobalt there are many small districts that contain silver ores resembling those of Cobalt, which mineralogically are rare and distinctive types. The copper, nickel, and silver deposits of the Lake Superior region in general may be characterized as ores deficient in sulphur or containing less sulphur than the common ores of these metals. The copper ores of Keweenaw Point, Michigan, carry the native metal; the nickel-copper ores of the Sudbury region, in Ontario, contain much pyrrhotite, a sulphide with less sulphur than the commoner iron sulphide pyrite. The silver ores of Cobalt and many districts near by are made up largely of arsenides and native metal. These deposits, though differing greatly as to structural relations and origin, are all in or near basic igneous rocks. The gold belt of California may be considered a metallogenic province, for its deposits are closely similar in composition and character. Because these deposits have been extensively eroded, many of them have furnished materials for enormous placers. In the Southwest, in Utah, Nevada, Arizona, and New Mexico, deposits of disseminated copper ores have been formed in connection with intrusions of granitic and monzonitic porphyries. These deposits have since been deeply eroded, and conditions have been favorable for much secondary concentration. With respect to both primary and secondary features they constitute a well-defined group.

The geologic processes that operate in any region, such as

deformation and denudation, affect the deposits it contains, and the deposits throughout the area in which the processes were operative may be expected to show certain similar features. Thus a great many deposits may be grouped in a relatively small number of provinces, and such a grouping is found to be useful for study and comparison. On the other hand, a relatively small area may contain deposits of totally different character formed at different times or even in the same geologic epoch. The regional grouping is useful, however, if differences of age and origin of deposits are properly recognized.

Metallogenic Epochs.—A metallogenic epoch is a division of geologic time. Ore deposits have been forming since the earliest periods recorded in the rocks, and they are forming today, but they have not formed at an equal rate throughout the geologic ages. Just as they have been concentrated regionally in provinces and subprovinces, so also they have formed more abundantly during one period or another. Iron deposits were formed most abundantly in North America in pre-Cambrian time, especially in the later Huronian epoch, but they formed abundantly also in the Clinton epoch of Silurian time and less abundantly in the Devonian, Carboniferous, and later periods. Gold deposits[1] were formed in the pre-Cambrian, early Cretaceous, early Tertiary, and middle Tertiary epochs. Silver deposits also were abundantly formed in pre-Cambrian and especially in Tertiary time. Many copper deposits were formed in the United States in pre-Cambrian, Cretaceous, and early Tertiary time, but only sparingly in the middle and late Tertiary. The age relations of deposits of the principal metals are mentioned in the following chapters, where deposits of the metals are treated separately.

Sources of Thermal Metalliferous Waters.—Studies of the composition of the metalliferous deposits and of the nature of hydrothermal alteration along fissures throw light on the composition of the metalliferous solutions that have deposited ores. The hot waters circulating in the fissures have deposited potassium, heavy metals, boron, fluorine, carbonates, sulphates, and other compounds. Many regions where igneous rocks have lately been intruded contain hot springs. Nearly all these

[1] LINDGREN, WALDEMAR: The Geological Features of the Gold Production of North America. Am. Inst. Min. Eng., *Trans.* vol. 33, pp. 790–845, 1903; Metallogenetic Epochs. *Econ. Geol.*, vol. 4, pp. 409–420, 1909.

springs carry alkali chlorides, and many carry carbonates and sulphates. A few carry also boron and fluorine; at some of them hydrogen sulphide and carbon dioxide gas escape. Some of these hot springs issue from fissures where ores are probably being deposited today, and it is believed that the waters of the hot springs are closely similar to the residues of solutions such as have deposited certain metalliferous veins.

Ascending hot waters vary considerably in composition,[1] and the wall-rock alterations they accomplish likewise show great variations. The conclusion is justified that ascending thermal waters[2] in general are complex solutions, containing varying amounts of sodium, potassium, alkaline earths, and heavy metals dissolved as chlorides, carbonates and sulphides, and subordinately as boron and fluorine compounds and sulphates.

Epigenetic ores have been grouped in six classes. They are deposited by aqueous solutions, hot and cold. Pegmatites and contact-metamorphic deposits are formed by solutions, either liquid or gaseous, that have emanated from cooling magmas. Ore bodies formed by cold solutions are deposited mainly by waters of meteoric origin—that is, by rain water that has sunk into the ground. The three classes of vein deposits—those formed in the deep zone, at moderate depths, and at shallow depths—are supposed to have been deposited by hot solutions, because such deposits are essentially confined to areas where igneous rocks are present, and along them the wall rocks show characteristic alterations unlike the changes that are known to result from weathering.[3]

Many deposits of this character have been formed below impervious beds, as if the solutions that deposited them had been halted in their upward journey by those beds. Others

[1] Emmons, W. H., and Harrington, G. L.: A Comparison of Waters of Mines and of Hot Springs. *Econ. Geol.*, vol. 8, pp. 653–669, 1913.

Hodge, E. T.: The Composition of Waters in Mines of Sulphide Ores. *Econ. Geol.* vol. 10, pp. 123–139, 1915.

[2] Tolman, C. F., Jr., and Clark, J. D.: The Oxidation, Solution, and Precipitation of Copper in Electrolytic Solutions and the Dispersion and Precipitation of Copper Sulphides from Colloidal Suspension, with a Geological Discussion. *Econ. Geol.*, vol. 9, pp. 559–592, 1914.

[3] Steidtmann, Edward: A Graphic Comparison of the Alteration of Rocks by Weathering with Their Alteration by Hot Solutions. *Econ. Geol.*, vol. 3, pp. 381–409, 1908. Stephenson, E. A.: Studies in Hydrothermal Metamorphism. *Jour. Geol.*, vol. 24, pp. 180–199, 1916.

extend downward for thousands of feet. They do not show the vertical zonal arrangement of minerals that characterizes many ore bodies formed or altered by descending cold solutions. For these and other reasons the solutions that deposited them are supposed to have been ascending.

The sources of such hot ascending solutions have been the subject of much controversy.[1] Some maintain that the thermal metalliferous waters are in the main of meteoric origin—that they are ordinary ground waters that have soaked into the earth and become heated by coming into contact with igneous bodies and thus, being hot, are active solvents of any metal contained in the rocks through which they move.[2] It is believed by most investigators, however, that the hot metalliferous solutions are contributed in part if not mainly by cooling igneous rocks.

[1] POSEPNY, FRANTZ.: The Genesis of Ore Deposits. Am. Inst. Min. Eng. *Trans.*, vol. 23, pp. 197–369, 1893.

[2] Most students of ore deposits advocated this theory of deposition in the period from 1850 to 1900. One of the most able expositions of this view appearing in recent years is that of Lawson, who summarizes the field evidence bearing on the problem. LAWSON, A. C.: Ore Deposition in and near Intrusive Rocks by Meteoric Waters. Cal. Univ. *Pub.*, vol. 8, pp. 219–242, 1914.

CHAPTER X

BUILDING MATERIALS

Building Stones.—Practically all hard rocks are used for building or for ornamental purposes. To be desirable for such uses a stone should have a pleasing color, satisfactory structure, strength, durability, and uniform texture and for use in a moist country it should have low porosity The color is a matter of taste and fashion. At present the lighter shades are more desirable than the darker ones. Most stone used in the main courses of buildings has strength far beyond that required of it, but if the stone is to be used for window caps or near other openings where stresses are unequal, its strength must be ascertained more precisely. Blocks near doors and windows, sill blocks, and caps are frequently broken in buildings. Strength tests are made by measuring the force necessary to crush a block of stone in a testing machine. Tests of transverse strength—that is, strength to withstand pressure applied unequally at different places—are made by supporting the two ends of a bar of stone and applying a force between the two supports.

Durability depends on several qualities. In general, fine-textured rocks, are more durable than coarse-textured rocks, especially sandstone and marble, although this is not universally true. Certain minerals are undesirable in building stone—particularly pyrite and other iron sulphides, because they oxidize, staining the rock yellow, and as they are soluble the surface becomes pitted. Moreover, sulphuric acid, formed by oxidation (p. 252), dissolves the stone, especially limestone. Nearly all igneous rocks and many sedimentary rocks contain some pyrite. A little, say about 0.3 per cent., if disseminated in the rock is not objectionable, but if it is concentrated in seams and veinlets it oxidizes and weakens the structure.

Mica is considered undesirable when it forms nodules and bunches in granite, because it renders the stone unsightly. In some quarries mica "knots" cause considerable waste. Small amounts of mica disseminated in the rocks are not injurious nor

undesirable. Mica schists have been used very effectively in certain cities to produce the rough surfaces that are preferred by some. In marble, chert is injurious because it is cut and polished with more difficulty than the calcite, and moreover its presence causes the limestone to weather unevenly.

Freezing and thawing tests are sometimes made. The stone is soaked in water and the effects of freezing noted. Instead of water, a saturated sodium sulphate solution is sometimes used to simulate the effect of freezing by crystallization of the sulphate in the rock pores. The value of this test, however, has been questioned. Absorption tests also have value for rocks to be used in structures exposed to water, and heat tests for rocks exposed to fire.[1]

Aside from the laboratory tests, valuable information may be obtained by studying a stone in the quarry and noting the effects of weathering on it, and also by studying the effects of weathering on buildings of known age. There is a great difference in the durability of stones. Some will weather badly in less than 20 years; others endure for centuries.

Chemical analyses are not especially valuable for showing the desirability of a stone for building. Microscopic examinations are sometimes useful, as they disclose the minerals contained in the rock. It is more important to ascertain the larger structural features, particularly the bedding, jointing, and sheeting. Many quarries are profitable because the joint systems are favorably spaced. For monoliths there should be but two systems of joints spaced fairly far apart. For paving blocks, closely spaced sheeting is desirable. Joint systems that make angles of 45° or less with other systems are objectionable, for they break the rocks into sharp wedges that must be trimmed.

A plane along which a granite may be easily broken is called the rift. Some rocks that appear to be perfectly homogeneous are found to be more readily broken in one direction than in others. When such planes lie in two directions, one is frequently called the rift and the other the run or grain of the rock. Some such planes are probably incipient fracture planes; others are probably due to strain, but they are little understood.

In considering the opening of a quarry, aside from the quality of the stone, cost of operation is an important factor. It is

[1] McCourt, W. E.: Fire Tests of Some New York Building Stones. N. Y. State Mus. *Bull.* 100, pp. 1–36, 1906.

determined in part by the jointing, bedding, and other features mentioned above. The demand for the stone, the ease of quarrying, the character of competing quarries, transportation facilities, and freight rates also are obviously to be considered. The quarry should have sufficient material available so that its product once established in the market may be supplied through a period of years. Among undesirable features in granite are knots, inclusions, dikes, hair lines (small dikes of dark rocks), quartz veins, pegmatite areas, pyrite lumps, and sheeting too closely spaced. Objectionable features in sandstone and limestone are clay seams too closely spaced, too much clay in the rock, shattered zones, pyrite areas, and mica bands.

Some stones change color on weathering and will change when placed in a building. Such changes may be noted in the stone on exposed faces in a quarry or in outcrops, or better still on surfaces of buildings made of the stone.

The building, ornamental, and other stone produced in the United States in 1920 had an estimated value of $120,500,000. An adequate presentation of the distribution of building stone in the United States would involve a discussion of the regional geology of the whole country, a subject too extensive to be included in this volume. General papers with bibliographies are mentioned below.[1]

Granite.—As a trade name granite is sometimes used to include most crystalline rocks of igneous or metamorphic origin that are

[1]Burchard, E. F.: U. S. Geol. Survey *Mineral Resources*, 1909–1912.

Ries, Heinrich, and Watson, T. L.: "Engineering Geology," pp. 428–492, New York, 1914.

Merrill, G. P.: "Stones for Building and Decoration," New York, 1903.

Eckel, E. C.: "Building Stones and Clays," New York, 1912.

Ries, Heinrich: "Building Stones and Clay Products," New York, 1912.

Buckley, E. R., and Buehler, H. A.: The Quarrying Industry of Missouri. Mo. Bureau of Geol. and Mines, 2*d ser.*, vol. 2, 1904.

Buckley, E. R.: On the Building and Ornamental Stones of Wisconsin. Wis. Geol. and Nat. Hist. Survey *Bull.* 4, 1898.

Bowles, Oliver: The Structural and Ornamental Stones of Minnesota. U. S. Geol. Survey *Bull.* 663, 225 pp., 1918.

Parks, W. A.: Report on the Building and Ornamental Stones of Canada, Province of British Columbia, Canada Dept. Mines, Mines Branch, vol. 5, pp. 236, 1917.

Parks, W. A.: Building and Ornamental Stones of British Columbia. Canada Dept. Mines, Mines Branch, *Summ. Rept.*, 1916, pp. 59–60, 1917.

dense and enduring. The Baraboo quartzites of Wisconsin are often spoken of as granite. Such use of the term is incorrect and is therefore to be discouraged. Granites are deep-seated holocrystalline igneous rocks, composed of quartz, feldspar, and mica. Because of their beauty and enduring quality they are in great demand for use as building stone and in monuments and other ornamental structures. Granite is used also for making paving blocks, curbing, and flagging and as crushed stone for concrete.

The granites of the Eastern United States are found at many places in a belt of crystalline rocks extending from Maine to Alabama. Granites are present also in Wisconsin and Minnesota and in the northern peninsula of Michigan; and there are small areas of granite in southeastern Missouri, in southern Oklahoma and in central Texas. In the West granites are found in an almost continuous belt along the Rocky Mountain front and in large areas farther west, including many mountain ranges in the Great Basin. Granites occur in extensive areas in the Pacific Coast States, and the variety granodiorite is prominent in the Sierra Nevada of California.

In Maine[1] granite is quarried at many places. The State is greatly favored by a deeply indented coast line, which gives cheap transportation by sea, and by recent glaciation, which in places cleaned off the rock. Wide spacing of joints makes it possible to quarry very large blocks, which are used for monolithic construction.

Granite is quarried for monumental work at Quincy, Massachusetts, Barre, Vermont,[2] and Westerly, Rhode Island.[3] In Maryland[4] granite is quarried for building stone near Baltimore, and a gneissic granite is quarried at Port Deposit.

[1] DALE, T. N.: The Granites of Maine. U. S. Geol. Survey *Bull.* 313, pp. 1–202, 1907.

BASTIN, E. S.: U. S. Geol. Survey Folio 158, Rockland, Me.

SMITH, G. O., BASTIN, E. S., and BROWN, C. W.: U. S. Geol. Survey Folio 149, Penobscot Bay.

[2] PERKINS, G. H.: Granite. Vt. State Geologist *Rept.* for 1900, pp. 57–77, 1900.

[3] DALE, T. N.: The Chief Commercial Granites of Massachusetts, New Hampshire and Rhode Island. U. S. Geol. Survey *Bull.* 354, pp. 1–228, 1908.

[4] MERRILL, G. P. and MATTHEWS, E. B.: The Building and Decorative Stones of Maryland. Md. Geol. Survey, vol. 2, pp. 47–125, 1898.

Granite is quarried in New Jersey,[1] at Mount Airy, N. C.,[2] at Stone Mountain, Georgia, and near Richmond, Virginia.[3]

In Wisconsin[4] granite is quarried at many places, and that obtained at Montello is especially well known. In Minnesota granite is quarried at St. Cloud and neighboring centers and at Ortonville. The granites of Minnesota have recently been described by Bowles.[5] Red granite is found in southeastern Missouri.[6] The joints are widely spaced, and large blocks are obtained. In Oklahoma[7] granite is found in the Arbuckle and Wichita mountains. Granite is quarried in the Granite Mountain quarry, Texas.[8]

Granite has been quarried in many western mountain states, among them Colorado, California, Arizona, and Utah.[9]

Other Igneous Rocks.—Many igneous rocks other than granite are used for building and for paving. Among them are serpentine, syenite, diorite, gabbro, basalt, and volcanic tuff. These rocks are described and the quarries from which they are derived are mentioned in the papers by Merrill and by Burchard, above noted.

Sandstone.—Sandstones are used extensively for building and are quarried in many States. The most productive area is the Triassic belt that extends from Massachusetts to North Carolina. In Connecticut and Massachusetts, along the Connecticut River Triassic sandstone has been quarried for many years and shipped to most of the large seaboard cities. A considerable number of

[1] Lewis, J. V.: Building Stones of New Jersey. N. J. Geol. Survey *Ann. Rept.* for 1908, pp. 53–124.

[2] Watson, T. L., Laney, F. B. and Merrill, F. J.: The Granites of North Carolina. N. C. Geol. Survey *Bull.* 2, 1906.

[3] Watson, T. L.: "Mineral Resources of Virginia," Richmond, 1907.

[4] Buckley, E. R.: Building and Ornamental Stones of Wisconsin. Wis. Geol. and Nat. Hist. Survey *Bull.* No. 4, pp. 1–554, 1898.

[5] Bowles, Oliver: Structural and Ornamental Stones of Minnesota. U. S. Geol. Survey *Bull.* 663, pp. 1–225, 1918.

[6] Buckley, E. R. and Buehler, H. A.: The Quarrying Industry of Missouri. Mo. Bur. Geology and Mines, vol. 2, ser. 2, pp. 1–371, 1904.

[7] Gould, C. N.: Structural Materials of Oklahoma. Okla. Geol. Survey *Bull.* 5, pp. 1–182, 1911.

[8] Burchard, E. F.: Structural Materials in the Vicinity of Austin, Texas. U. S. Geol. Survey *Bull.* 430, pp. 292–316, 1910.

[9] Burchard, E. F.: Stone Resources of the States West of the Rocky Mountains. U. S. Geol. Survey, *Mineral Resources* 1913, part 2, pp. 1335–1398.

the houses in New York City have been built of it. The Triassic sandstone[1] is reddish brown, breaks in large blocks at the quarry, and is easily worked. Some of it scabs off in building, but according to Merrill[2] this is due largely to the method of laying the stone, which is split thin, stood on edge, and used as a veneer for cheaper material. Laid with the bedding flat it is more enduring.

Sandstones that are not firmly cemented are not very desirable for building stones. They weather readily and become pitted, and are subject to further wear by particles of sand blown against them by the wind. The coarse cross-bedded blocks especially are subject to wear.[3]

Marble.—Marble is recrystallized limestone; it is used for building but more generally for ornamental stone and interior decoration.

In Vermont marble for ornamental purposes has been quarried since the country was first settled, and the quarries now supply a large part of the ornamental stone of the country.[4] The quarries of Rutland County are noteworthy. The Vermont marbles are gray or white and are commonly traversed by green or brown veins. Marbles are quarried also in Massachusetts, New York, Maryland, and in Pickens County, Georgia,[5] in eastern Tennessee,[6] and in Colorado.

Onyx is lime carbonate deposited in caves or at the orifices of hot springs. It is used for interior decoration. Most of the onyx used in the United States[7] comes from Mexico. Some onyx, however, is quarried in Arizona.

[1] HOPKINS, T. C.: Brownstones of Pennsylvania. U. S. Geol. Survey *Eighteenth Ann. Rept.*, part. 5, pp. 1025–1043, 1897.

[2] *Op. cit.*, p. 137.

[3] This is shown by Pillsbury Hall, on the campus of the University of Minnesota.

[4] PERKINS, G. H.: Marble. Vt. State Geologist *Rept.* for 1900, pp. 38–43. See also reports for other years.

[5] MCCALLIE, S. W.: Marbles of Georgia. Ga. Geol. Survey *Bull.* 1, pp. 1–87, 1904.

GORDON, C. H.: The Marbles of Tennessee. Tenn. Geol. Survey *Bull.* 2D, pp. 1–33, 1911.

GORDON, C. H.: Nature and Origin of the Holston Marble Formation in East Tennessee. Tenn. Acad. Sci. *Trans.*, vol. 2, p. 92, 1912.

[7] DEKALB, COURTENAY: Onyx-Marbles. Am. Inst. Min. Eng. *Trans.*, vol. 25, pp. 557–569, 1895.

GORDON, C. H.: Cave Marble (cave onyx) in Tennessee. Resources of Tennessee, vol. 2, pp. 307–317, Tenn. Geol. Survey, 1912.

Limestone.—Limestone is used for many purposes, including the manufacture of cement and lime (see p. 294). It is used also for building and construction and is produced in many States. The Bedford limestone of Lawrence County, Indiana, the Kasota stone of Minnesota, and the crystalline limestone mined at Carthage, in southwestern Missouri, are well known.

Slate.—When mud and clay are deeply buried and subjected to pressure, they generally assume a slaty cleavage by virtue of which they may be separated into thin, tough plates. These plates are commercially termed slates and are utilized for roofing,



FIG. 179.—Quarry in Cambrian green slate, Middle Granville, New York. (*After Dale.*)

stair treads, wainscoting, laboratory tables, etc. When a clay is changed to slate by pressure or dynamic metamorphism, the stable minerals like quartz are rearranged so that the long dimensions of the particles lie in one plane, and new minerals such as actinolite, tremolite, mica, and chlorite, developed from kaolin and other minerals in the clay, will form with their long axes in the same plane as the long dimensions of the mineral fragments (see p. 241). The slate will split most readily along such a plane. Igneous tuffs and other material of igneous origin may also be changed by dynamic metamorphism into slaty rocks, but nearly all the commercial slates are of sedimentary origin.

Slates are black, green, gray, or red, their color depending on that of the constituent minerals. Some slates change color on long exposure, particularly many green slates, which become bleached, and many red slates, which tend to become brown. Black slates and gray slates are generally more nearly permanent in color. Moderate bleaching is not very objectionable unless the slate becomes spotted. For roofing, a slate should be of nearly permanent color and should not break on being punched. Lime carbonate, iron carbonate, and pyrite are objectionable constituents.

Slates (Figs. 179, 180) are formed in areas where the rocks have been subjected to dynamic metamorphism. They are found in

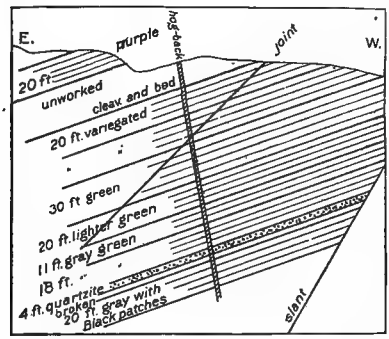


FIG. 180.—Cross-section of Eureka slate quarry, Poultney, Vermont. The quarry produces "unfading green" and "variegated" slate. (*After Dale.*)

the Appalachian region from Maine to Alabama. Beds that are but little worked occur in Michigan, in Minnesota, and in the western Cordillera. The value of the slate produced in the United States in 1919 was $5,065,000.

References to general papers that contain bibliographies are given below.[1]

Prepared Stone Roofing.—In recent years there has been a demand for roofing made of paper felt, asphalt, and crushed

[1] DALE, T. N.: Slate Deposits and Slate Industry of the United States. U. S. Geol. Survey *Bull.* 275, 1906, also *Bull* 586, 1914.

RIES, HEINRICH: "Building Stones and Clay Products," New York, 1912.

DRESSER, J. A.: On the Slate Industry in Southern Quebec. Canadian Min. Inst. *Quart. Bull.* No. 15, pp. 71–85, 2 pls., 1 fig., June, 1911. *Canadian Min. Jour.*, vol. 32, pp. 584–590, 1911.

rock. The asphalt or residue from oil refining, such as is used for road dressing, is applied hot to a surface of heavy paper felt, and the rock, previously crushed to small particles and sized, is applied to the hot tarred surface and pressed down by heavy rolls. The material is used in strips or is cut to form shingles Used with stucco walls this roofing is very effective, and it is not readily inflammable. Low-grade mica scrap and low-grade asbestos are used to make gray roofing, red shale or slate and other red rocks for red roofing, and green shale or slate for green roofing. Bright colors are in demand. Red rocks are obtained at many places, but green rocks suitable for roofing material are not so common. The waste of slate quarries has been used, and well-indurated green shales are in demand. The medium shades are desired, but a light-green material becomes darker by absorbing oil from the dark asphaltic mixture. In testing a rock to ascertain its availability for making artificial roofing, a drop of heavy oil should be applied to a small particle; any change of color will be apparent.

Cement.—Cement[1] is made by fusing mixtures of oxides of calcium, aluminum, and silicon. When the clinker is ground and mixed with water it sets to a strong, hard, solid mass. The three oxides need not be present in exact proportions, but within certain limits the mixture may vary. Some limestones containing considerable clay are of suitable composition for cement without the

[1] ECKEL, E. C.: Portland Cement Materials and Industry in the United States. U. S. Geol. Survey *Bull.* 522, 1913.—"Limes, Mortars, and Cements," New York, 1907.

BURCHARD, E. F.: U. S. Geol. Survey *Mineral Resources*, 1911, part 2, pp. 485–515, 1912.

RIES, HEINRICH, and ECKEL, E. C.: Lime and Cement Industries of New York. N. Y. State Mus. *Bull.* 44, 1901.

BLEININGER, A. V.: The Manufacture of Hydraulic Cements. Ohio Geol. Survey, 4th series, *Bull.* 3, 1905.

RANKIN, G. A., and WRIGHT, F. E.: The Ternary System CaO–Al_2O_3–SiO_2. *Am. Jour. Sci.*, 4th ser., vol. 39, pp. 1–79, 1915.

BEYER, S. W., and WILLIAMS, I. A.: The Materials and Manufacture of Portland Cement. Iowa Geol. Survey, vol. 17, pp. 29–89, 1907.

The Geology of the Iowa Quarry Products. Iowa Geol. Survey, vol. 17, pp. 201–588, 1907.

BASSLER, R. S.: Cement Materials of Western Virginia. *Econ. Geol.*, vol. 3, pp. 503–524, 1908.

LANDES, HENRY: Cement Resources of Washington. U. S. Geol. Survey *Bull.* 285, pp. 377–383, 1906.

addition of other material. The cements made of such limestones are termed natural cements. If the mixture is made artificially it is called Portland cement. The hardening is not brought about by the addition of material from the atmosphere, as when mortar hardens by the addition of CO_2, but is due to the formation of hydrates of calcium and aluminum. Portland cement and some natural cements will harden under water as well as in air.

Analyses of calcareous rock to be used for natural cements should show between 15 and 40 per cent. of clay and silica and not more than a small percentage of magnesia. After burning only a small percentage of free lime should be present.

Portland cement is made by mixing a calcareous material, such as limestone, chalk, or marl, with a siliceous and aluminous material, such as clay, shale, slag, or mud. As it is possible to vary the proportions of the substances used the mixture is made to approach closely a desirable standard composition that has been found satisfactory by previous experimentation. Portland cement is generally superior to most natural cements, because the mixture is more easily controlled and is nearly uniform. The mixture before burning generally consists of about 75 per cent. $CaCO_3$, not more than 5 per cent. $MgCO_3$, 12 to 15 per cent. SiO_2, and 4 to 7 per cent. Al_2O_3. Between 1 and 2 per cent. each of Fe_2O_3, K_2O, and organic matter are commonly present. None of these substances are detrimental except MgO, which, if running above 6 per cent., at least under some conditions, will weaken the product. Iron oxide and potassium oxide, on the other hand, are desirable, for they lower the temperature necessary for sintering. On burning CO_2 and H_2O are driven off, and the percentages of other substances in the clinker are thereby increased about one-half.

Cement making consists of three steps—(1) grinding and mixing, (2) clinkering, (3) grinding the clinker.

In grinding, chert and other siliceous matter in the limestone are generally considered undesirable, as they increase the cost. Recently improvements in grinding machines have reduced the cost of grinding, and there is an increasing tendency to utilize the purer limestone and the slags, instead of softer marl and argillaceous limestone. In burning the cement mixtures, the temperatures employed are generally above 1500°F., depending on the composition of the mixture and the nature of the burning apparatus. The mixture contains considerable CO_2 in

carbonates, and this is driven off at about 750°F. to 1,400°F., increasing porosity and decreasing volume of material. In burning complete fusion is avoided, for on fusion the constituents might segregate. Incineration is accomplished, therefore, not in a shaft like those employed in smelting the metals, but, in many plants, in long revolving cylinders, tilted a little so that the material moves automatically from the intake at the upper end to the point of discharge at the lower end. Flame, generally kindled by powdered coal or oil, is introduced at the lower end and escapes at the upper end of the cylinder through a flue provided there. Some cement kilns are 240 feet long.

The clinker, which comes out as small masses, is ground in ball mills. Fine grinding is necessary, as cement that is not finely ground will not set.

Natural cement is made by burning impure limestone containing 15 to 40 per cent. silica, alumina, and iron oxide. The temperature required is not much above that at which lime is burned, and kilns like the ordinary limekilns may be used. Carbon dioxide is driven off, and lime silicates, aluminates, and ferrates are formed. The ground clinker does not slake and sets slowly under water.

The production of cement in the United States in 1920 was 96,944,000 barrels, valued at $194,513,000.

Mortar.—The function of a mortar is to act as a binding material, converting the blocks of a wall or other structure into a coherent mass. It is made by mixing from 1 to 5 parts of clean sand with 1 part of slaked lime or cement. Generally cement is considered more durable for buildings, and in some that are centuries old it still endures.

Concrete.—Concrete is a mixture of sand, cement, and gravel or crushed stone, in which the cement acts as a mortar. Because the material can be poured into forms and thus handled cheaply, its use is rapidly increasing. The principle that the total pore space in a rock depends not on the size of particles but upon uniformity of size, being greatest when particles are of equal size (see page 259), is important in this connection. So long as the cement makes into a coherent mass the various particles, the less required the better, provided the other materials used in the concrete mixture are sufficiently strong. In the larger concrete structures it is considered desirable to introduce large irregular blocks of stone, which generally decrease cost and

increase strength. Even in neat cement not all of the mixture becomes hydrated to form new compounds, but the part that does is sufficient to bind the other parts together firmly. Sand is sometimes ground fine and added to cement. It should not be regarded as an adulterant, because a small amount may even add to the strength of the product, especially if the sand grains are angular and thus interlock and present large surfaces of contact.

Pozzolan Cement.—Pozzolan cement is made by mixing slaked lime with finely ground clayey material, finely ground furnace slag, or volcanic ash. It is not calcined, and the mixture is little more than a lime mortar. The material is cheap but is not recommended for structures intended to endure, although in Italy some houses made of such material have had a long life. Pozzolan cement should not be confused with Portland cement made of slags from iron blast furnaces. In making Portland cement from slags, the slags are ground and other material is added to give a suitable mixture. After sintering the clinker is ground as in making Portland cement from other materials.

Distribution of Cement Materials.—It is desirable that limestone to be used for making Portland cement should be nearly homogeneous in composition, for then the composition of mixtures may be very easily controlled. At some places, however, the beds that are used show considerable variation in composition, both along and across the strike. Magnesian beds, or those containing too much clay, are avoided, or when they are used purer limestone is added. A limestone with some clay is preferable to a pure limestone if the clay is evenly distributed, because it simplifies mixing.

Limestones suitable for making Portland cement are widely distributed in the United States; detailed accounts of their distribution are given in papers by Burchard[1] and Eckel.[2] The Lehigh Valley district of Pennsylvania[3] supplies about one-third of the product of the United States. The rocks are of Paleozoic age and are closely folded. The Trenton limestone and Hudson River shale supply much of the cement material. The lower part

[1] Burchard, E. F.: U. S. Geol. Survey *Mineral Resources*, 1910, part 2, pp. 489–535, 1911.

[2] Eckel, E. C.: "Limes, Mortars, and Cements," New York, 1907.

[3] Peck, F. B.: Geology of the Cement Belt in Lehigh and Northampton Counties, Pennsylvania. *Econ. Geol.*, vol. 3, pp. 37–76, 1908.

of the Trenton is nearly pure limestone but contains some dolomite beds that are avoided as far as practicable in quarrying. The upper part of the Trenton is argillaceous limestone, some of which has the composition of natural cement rock. Mixtures of the lower and upper beds provide a material of suitable composition. The Lehigh belt of Trenton limestone extends into New Jersey, where also this formation supplies much material for cement.

In eastern New York Portland cement is made of Ordovician and Silurian limestones mixed with surface clay. Devonian beds are used in Kentucky, Ohio, and Wisconsin. In Kansas Mississippian, Pennsylvanian, Permian, and Cretaceous limestones are used. In Texas and Arkansas Cretaceous shales and limestones supply material for Portland cement. In the glacial belt, especially in Michigan, Indiana, and Ohio, fresh-water marls are used with Pleistocene clays. The marl forms in the lakes through the agency of small plants. It is commonly incoherent and in some lakes is pumped out and dried for cement making. Some of the lakes are drained, and the partly dried marl is excavated with steam shovels.

Rocks for natural cement are quarried from the Silurian beds in Ulster, Schoharie, Erie, and Onondaga counties, New York. Natural cement rocks are obtained also in Maryland and Virginia, at Utica, Ill., near Milwaukee Wis., and Mankato, Minn., and at several other localities.

Limestone and Lime.—Limestone is a common sedimentary rock that is deposited in the sea and to a less extent in fresh waters. It is formed mainly through the agency of lime-secreting organisms and to some extent probably by direct precipitation. It has an important place in the arts. Its use as a building stone has been mentioned (p. 292), and it is a constituent of mixtures used for making cement (p. 294). It is extensively used in furnace mixtures as a flux for iron, copper, precious metals, and other ores. It is ground and used as a fertilizer, particularly for correcting acid soils.

Lime is made by heating limestone to about 800°C. Impure limestones are heated to a higher temperature. At such temperatures the limestone loses CO_2 and becomes "quicklime," CaO. When water is poured on quicklime chemical action takes place: $CaO + H_2O = Ca(OH)_2$. This reaction increases volume: about 32 parts of water is added to 100 parts CaO. As

calcium hydroxide is soluble it is used extensively in the arts to neutralize acids and to make solutions alkaline. Large amounts are used in sugar refining, in cyaniding gold ores, and in tanning. Quicklime is used in the manufacture of alkalies and bleaching powders, etc. It is the cheapest alkali, just as sulphuric acid is the cheapest acid, and it has a correspondingly important position in the industries.[1]

Limestone that is to be converted to calcium hydroxide is commonly crushed at the quarry and transported as the stone. The sizing of limestone to be burned for chemical purposes is important. If the lumps are too small they are overburned; if too large they are not thoroughly burned and some of the limestone remains as calcium carbonate. Some kilns use lumps about 6 inches in diameter. If there are among them lumps the size of walnuts, these are burned so that they remain undissolved for days after the lime made of coarser lumps has gone into solution or emulsion. Sugar refiners use large amounts of lime for burning. A pure limestone is generally required.

In the process of manufacturing sugar from the juice of the sugar beet a molasses is formed which contains much sugar. The molasses is heated with calcium hydroxide and subsequently cooled to 15°C. Sugar is precipitated as tricalcium sucrate, from which it is subsequently recovered by refining. The method is said to be inferior in some respects to the strontia process (p. 368), partly because the solution must be kept cool during the precipitation, but it is more generally used in the United States, probably because limestone is more readily available than strontium salts.

Common lime mortar is made by mixing sand, quicklime, and water. It is hardened by CO_2 of the air:

$$Ca(OH)_2 + CO_2 = CaCO_3 + H_2O$$

A crust first forms, enough to hold the bricks or stones, and very slowly the carbonation extends inward. The calcite crystals form only a matrix or "groundmass" for the particles of sand, just as hydrates form the matrix in Portland cement mixtures. The sand adds strength and decreases shrinkage; without sand, cracks will form on drying. Lime mortar does not harden in damp places, and its use is not recommended for cellars and deep

[1] BURCHARD, E. F., and EMLEY, W. E.: The Source, Manufacture, and Use of Lime. U. S. Geol. Survey, *Mineral Resources*, 1913, part 2, pp. 1509–1593, 1914.

foundations. Calcium carbonate, if nearly pure makes a lime that slakes readily ("fat" lime). If magnesia is present it slakes more slowly ("meager" or "cold" lime). This is not always undesirable, and more magnesium is allowable than in limestone to be used for making Portland cement. For many structural purposes magnesian lime is preferable. Some lime is hydrated, dried, and powdered before being marketed.

With increasing alumina and silica lime grades into natural cement. Some argillaceous limestones, heated somewhat above the point of decarbonation, yield bricklaying cement that is said to be superior to common lime for making mortar.

Limestones suitable for lime are widely distributed. In a search for deposits of limestone to supply lime or cement for a certain market it is advisable to consult geologic maps of regions near by[1] and ascertain the lithologic character of the formations. Analyses will show what beds are available. Some hundreds of analyses of limestones quarried in the United States are recorded by Burchard.[2]

Marl.—Marl is unconsolidated, generally earthy calcium carbonate. It is found at many places in the deposits of glacial lakes in Minnesota, Michigan, and Wisconsin, as already noted (p. 298) and in Michigan it has been used for making Portland cement. In these States it has been deposited chiefly through the agency of the *Chara* plants (stoneworts), which abounded in the lakes. Some of the marls are made up chiefly of fragments of snail shells. As a rule the marl when dug contains water to the extent of more than half its weight. Because so much inert material must be handled and because most of the deposits are small compared with limestone beds, marl has not come into general use as a source of quicklime. Possibly some can be used for treating acid soils near the places of its occurrence.

Gravel and Crushed Stone.—Gravel is used extensively for road-building material (road metal), for mixing with sand and cement to make concrete, for roofing, etc. The gravel of all hard rocks is used. All dense igneous rocks that are firm and not altered by weathering are satisfactory. Among the sedimentary rocks quartzites and limestones are preferred. Soft sandstones,

[1] Willis, Bailey: Index to the Stratigraphy of North America. U. S. Geol. Survey *Prof. Paper* 71, 1912 (contains extensive references).

[2] Burchard, E. F.: U. S. Geol. Survey *Mineral Resources*, 1911, part 2, pp. 658–680, 1912.

shales, shaly limestones, and shaly sandstones are generally too soft to wear satisfactorily. Much of the gravel of the northern part of the United States is obtained from deposits of glacial drift. Where much sand and clay are present, the gravel is screened and sorted. If there are many shale fragments the gravel is regarded as unfit for concrete work or road metal. At some places the shale is picked out or washed out.

Rumbler tests are made on gravel to ascertain its wearing qualities. The material is loaded into a steel barrel with steel balls, and the barrel is rotated at a regulated speed. The time required to wear down the material is noted, and its wearing quality is compared with that of material of known quality.

Crushed stone is used for the same purposes as those for which gravel is used and is tested in a similar manner. These subjects are treated in textbooks on the testing of materials, and their distribution is discussed in annual volumes of "Mineral Resources of the United States," published by the United States Geological Survey.

Sand.—Sand[1] is used in large amounts for making concrete, mortar, brick, and glass. Smaller amounts are used for molding sands, for making sandpaper, for sanding painted buildings, for the sand blast, for making filters, etc.

A foundry sand is one used for making molds for casting metals into desired forms. Sands of fine texture, containing a small amount of clay, are commonly used. There should be enough clay to hold the sand together and not so much that the mold on drying will shrink excessively. The mixture must not flux easily, or the mold will collapse, and it should be sufficiently porous to allow gases to pass through it readily. Artificial binders are mixed with many sands. Dextrin, molasses, and starch are commonly used. Glass sand is mentioned on p. 375.

[1] CANDIT, D. D.: The Petrographic Character of Ohio Sands with Relation to their Origin. *Jour. Geol.* vol. 20, pp. 152–163, 1912.

RIES, H., and GALLUP, L.: Moulding Sands of Wisconsin. Wis. Geol. and Nat. Hist. Survey *Bull.* 15, pp. 197–247, 1906.

STONE, R. W.: Statistical reports in "Mineral Resources of the United States."

RIES, H., and ROSEN, J. A.: Reports on Foundry Sands. Mich. Geol. Survey *Rept.*, 1907, pp. 33–85, 1908.

COLE, L. H.: The Occurrence and Testing of Foundry Moulding Sands. Canadian Min. Inst. *Trans.*, vol. 20, pp. 265–291, 1917.

Sand-lime Brick.—Sand-lime brick[1] are made by mixing sand and lime, molding, and exposing the brick to air or steam. When exposed to air the lime acts as a mechanical binding substance; under the influence of the carbonic acid and moisture of the air, carbonate of lime is formed, which surrounds the sand particles and unites the mixture in one mass. With steam at a high temperature chemical combination takes place between the silica contained in the sand and lime. This chemical reaction must be sufficiently active that the mixture may form a whole whose single elements become intimately united by a new chemical compound.

The silico-calcareous compound can be obtained in a few days or even a few hours according to the temperature—that is, the pressure of steam, and the combination can be brought to such a degree of perfection that the stones can be used immediately as a building material.

Clay.—Clay[2] is a term used without any very definite mineralogic significance to describe material that is plastic when wet and that when shaped and dried will retain its shape and when burned will become hard. The principal constituent of most clays is kaolinite, $H_4Al_2Si_2O_9$, or a colloid of approximately similar composition, but fragments of quartz, iron oxides, silicates, and other minerals are generally present. Kaolin is the commonest product of weathering of aluminum minerals such as feldspars and micas. Nearly all igneous rocks contain aluminum minerals, and kaolin is almost invariably formed as a result of

[1] STOFFLER, ERNEST: Silico-calcareous Sandstones, Introduction, pp. 1–36, London.

[2] RIES, HEINRICH: The Clays of the United States East of the Mississippi River. U. S. Geol. Survey *Prof. Paper* 11, 1903. "Clays: Occurrence, Properties, and Uses," New York, 1908.

MERRILL, G. P.: "Rocks, Rock Weathering, and Soils," New York, 1906.

ECKEL, E. C.: "Building Stones and Clays," New York, 1912.

The technology and uses of clays, especially those of glacial origin, are summarized in *Bull.* 11 of the Minnesota Geological Survey, by F. F. GROUT and E. K. SOPER. A complete list of papers on clays would be too long for this volume. Bibliographies will be found in the volumes by RIES, MERRILL, and ECKEL, noted above; and in one by J. C. BRANNER (Bibliography of Clays and the Ceramic Arts. U. S. Geol. Survey *Bull.* 143, 1896).

BRANNER, J. C.: Clays of Arkansas. U. S. Geol. Survey *Bull.* 351, 247 pp., 1908.

MIDDLETON, JEFFERSON: U. S. Geol. Survey *Mineral Resources*, 1915, part 2, pp. 10, 12, 1916.

their weathering. Thorough weathering of feldspar-bearing pegmatites may yield high-grade kaolin deposits. Limestones also generally contain aluminum as kaolinite and by weathering form residual clays. Shales are clays that have been consolidated by pressure. On weathering they break down and again form clays. If a surface has long been exposed to weathering with little erosion, as happens when a region approaches base-level, soluble substances are almost completely leached out, and the residual clay remains. Ordinarily the parent rock may be found a few feet or rarely more than 50 or 100 feet below the surface. Such clayey substance or mantle rock commonly constitutes the soil of old unglaciated surfaces. Even sandstone and quartzite contain some clay, and their residual soils may be more aluminous than the parent sandy rocks. The formation of clays by weathering is indicated in Fig. 181.

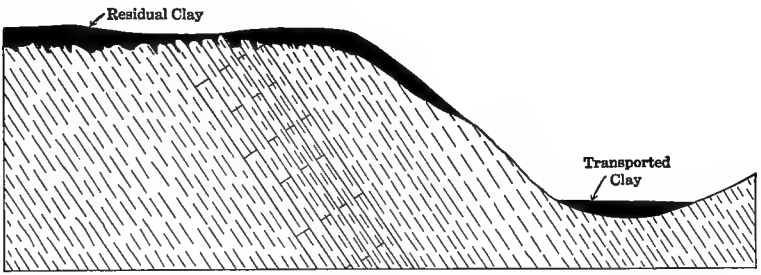


FIG. 181.—Sketch showing clay formed by weathering of shale and shaley limestone on a base-leveled surface. Uplift and erosion followed base leveling and some of the clay was transported and deposited in a valley nearby.

In normal erosion much of the weathered clayey material is carried by streams and deposited along rivers or in deltas. Through uplift or rejuvenation clay terraces may form. Where a weathered surface is rejuvenated, erosion of the upland is more rapid, and more clayey material is deposited.

Glacial till generally contains much clay, and where the till is worked over and sorted by glacial waters, clay deposits of considerable magnitude are commonly formed. Such deposits usually differ from residual clays in that they contain "rock flour," or material derived from the mechanical abrasion of rocks and not by weathering, which removes the more soluble constituents of rocks. Many glacial clays contain considerable lime carbonate and effervesce freely with acid.

The plasticity of clays is probably due to colloidal substances or "gels" that they contain. Halloysite and pholerite, colloidal aluminum silicates more highly hydrated than kaolin, are probably present in most clays and doubtless are important in connection with plasticity.[1] Grout[2] believes that molecular attraction also plays a part in rendering clays plastic.

According to Logan, kaolin is formed through the agency of bacteria. Laboratory experiments showed that sulphur bacteria secrete kaolin, and in southern Indiana kaolin is being formed today by sulphur bacteria.[3]

Kaolin and clay deposits have been formed in many past geologic ages, hence they are found in the older rocks covered by the later rocks, especially at unconformities.

Analyses of clays do not go very far to show their availability. Kaolin contains silica, 46.5 per cent.; aluminum, 39.5 per cent. and water, 14 per cent.; but few clays approach kaolin closely in composition. The china clays and fire clays are nearest to kaolin; as a rule they result from weathering of feldspathic igneous rocks or of sedimentary rocks. Alkalies, lime, magnesium, and iron lower the fusing points of clays and render them useless as refractory material.

Burning tests are the most satisfactory tests of clays. Iron in clay on burning colors the brick red. It is counteracted by lime carbonate. Many glacial clays—for example, those of Milwaukee, Wis.—burn buff, owing to excess of lime. Too much lime, however, is undesirable, and limestone pebbles will cause the brick to crumble. Too much carbonaceous matter is also undesirable, as it causes bloating. Silica lowers shrinkage and plasticity. Sand may be added to clay where less fire shrinkage is desirable.

Fire clays are formed where the physiographic conditions are favorable for the leaching out of all materials other than kaolinite. Such conditions may exist where coal beds are formed. The ground waters, aided by vegetation, remove the more soluble substances. Thus fire clay is commonly found below a bed of

[1] CUSHMAN, A. S.: On the Cause of the Cementing Value of Rock Powders and the Plasticity of Clays. Am. Chem. Soc. *Jour.*, vol. 25, pp. 451–468, 1903.

[2] GROUT, F. F.: The Plasticity of Clays. *Idem*, vol. 27, p. 1037, 1905.

[3] LOGAN, W. N.: Kaolin of Indiana. Ind. State Dept. *Conservation Bull.* 6, 1920; *Jour. Geol.*, vol. 28, p. 470, 1920.

coal. At some places in the Missouri and Illinois[1] coal fields the bed of fire clay is removed and the coal is left as a support for the overlying material.

Aside from the residual clays and the sedimentary and glacial clays, loess, a wind-blown material, is used at many places for brickmaking.

In making brick, the following changes take place. The molded material is dried, with some shrinkage. On firing there is further shrinkage, the total decrease in volume commonly amounting to 10 per cent. or more. Combined water is driven off at about 450°C., and any organic matter will undergo combustion at temperatures somewhat higher. As the temperature is raised iron is oxidized, and if enough iron is present the brick becomes red. If carbonates are present carbon dioxide escapes. Incipient fusion takes place, and this hardens the mass. If the temperature is raised high enough the brick is vitrified, particularly the outer surface, which is hottest.

In the United States nearly every State has large supplies of clays. In the Coastal Plain region from New York south and along the Atlantic and Gulf coast to Texas transported clays are abundant. They are coast deposits later elevated above the water level. In the glaciated regions glacial clays abound. In the southern Appalachians and at some other places in the unglaciated regions residual clays are found. Shales and slates that represent clay beds of past geologic ages are also used at many places. The raw clay produced in the United States in 1920 amounted to 3,159,000 tons, valued at $12,094,000. The clay products of 1920 were valued at $364,220,000.

The uses of clays and clay products are well known.

Discussions of the technology of clays and descriptions of occurrences are given in the papers already cited.

[1] PURDY, R. C. and DEWOLF, F. W.: Investigation of Illinois Fireclay. Ill. Geol. Survey *Bull.* 4, pp. 129–176, 1907.

BUTLER, G. M.: The Clays of Eastern Colorado. Colo. Geol. Survey *Bull.* 8, pp. 1–353, 1914.

CHAPTER XI

MICA, FELDSPAR, GEMS, LITHIUM MINERALS, MONOZITE, GRAPHITE, AND QUARTZ

Mica.—Although mica is a common constituent of igneous rocks, of crystalline schists, of contact-metamorphic deposits and of some veins, the mica of commerce is derived from pegmatites. Most pegmatites are composed chiefly of quartz, feldspar, and mica. In the commonest type feldspar predominates, but in some pegmatites quartz is the principal constituent, and in a few mica is abundant. The micas[1] include muscovite ($H_2KAl_3Si_3O_{12}$), phlogopite ($H_2KAlMg_3Si_3O_{12}$), and biotite ($HKAl_2Mg_2Si_3O_{12}$), Iron also is commonly present in biotite, taking the place of aluminum or magnesium. Lepidolite, or lithium mica, is a source of lithium salts. The important commercial micas are muscovite and phlogopite.

Micas, especially muscovite, resist weathering. In some deposits mica is picked out of the clay and quartz of the weathered pegmatite; in others the unweathered material is mined.

As the value of mica depends partly upon its property of splitting into flat sheets, those deposits in which it is bent and twisted by dynamic metamorphism are less sought than the pegmatites that are not metamorphosed.

As a rule mica is not uniformly distributed in pegmatites but is found as books and foils in nests, locally developed. Besides feldspar and quartz, which generally constitute the bulk of the pegmatitic material, the mica-bearing rocks in places contain apatite, beryl, tourmaline, zircon, and garnet. Mica deposits are generally worked in a very simple fashion. The material is mined, sorted, and cut or trimmed by hand.

The properties that make mica valuable are its transparency, toughness, elasticity, cleavage, resistance to heat, and electrical nonconductivity.

[1] Sterrett, D. B.: Mica. U. S. Geol. Survey *Mineral Resources*, 1911, part 2, p. 1130, 1912 (includes bibliography).

Schmid, H. S.: Mica; Its Occurrence, Exploitation, and Uses. Canada Dept. Mines, Mines Branch 118, 411 pp., 1912.

The larger pieces of mica are used for making electric apparatus and glazing stoves and lamp chimneys. Smaller pieces are used in making "micanite" or built-up mica board, used chiefly for electric appliances.

The greatest use for mica is in the manufacture of electrical equipment (Fig. 182). For such purposes there is no satisfactory substitute. It is used for making resonators, condensers for wireless equipment, spark plugs, and magnetos. In making dynamos mica is generally used as an insulator; phlogopite is used as well as muscovite. Ground mica is used for making paints, wall paper, lubricants, building paper, etc. The United States in 1918 produced 1,644,200 pounds of trimmed mica,



FIG. 182*A*.—Preparing mica in India. Mica cutters at work. (*After Dixon.*)

valued at $731,810, and 2,292 tons of scrap mica, valued at $33,130. Large clear pieces of mica cut to dimensions of several inches square sell for $1 a pound or more, but low-grade material is cheap.

Nearly all the world's supply of mica is obtained in India, Canada, and the United States. India produces much the largest part. Mica deposits are found at many places in India, but the two chief producing regions are in Bengal and in the Madras Presidency. The mica-bearing region in Bengal is an area of gneiss, mica schists, tourmaline schists, hornblende rocks, and quartzites, with intrusive dikes of fine-grained diorite.[1] Conforming with the bedding of the schists from east to west are

[1] SMITH, A. M.: Mica Mining in Bengal, India. Inst. Min. and Met. (London), *Trans.*, vol. 7, p. 168–174, 1899.

numerous veins of granite pegmatite ranging from mere threads to dikes 20 feet in width. The veins contain quartz, large crystals of pink orthoclase, and crystals or "books" of muscovite. The quality of the vein varies with the nature of the adjacent

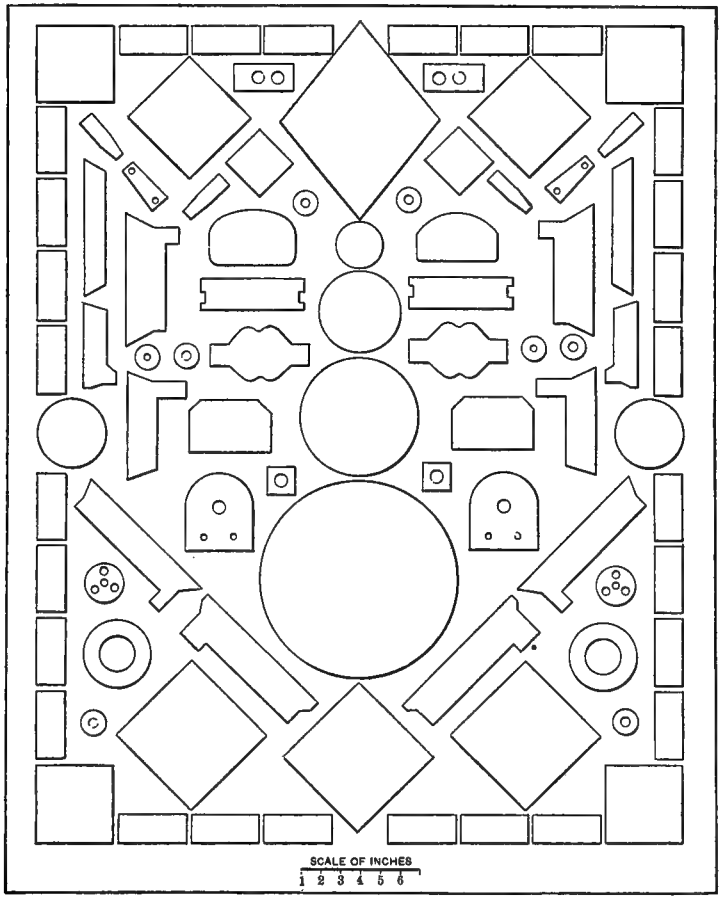


FIG. 182*B*.—Common forms of mica prepared for use. (*After Dixon.*)

rock. The mines have been worked by the natives for centuries and now supply material for American and European markets. Sheets as large as 24 by 18 inches are prepared.

In Canada[1] phlogopite is extensively mined in a district north

[1] SCHMIDT, H. S.: Mica, its Occurrence, Exploitations and Uses. Canada Dept. Mines, Mines Branch 118, pp. 1–411, 1912.

of Ottawa. It occurs in dikes or veins in gneiss and in limestone. Associated minerals are pyroxene, apatite, scapolite, calcite, titanite, molybdenite, and other sulphides. These deposits are probably pegmatite veins of an unusual type and nearly related deposits of contact-metamorphic origin. Apatite-scapolite veins probably of similar genesis are found also in Norway.

The mica produced in the United States[1] comes from New England,[2] the southern Appalachian region,[3] the Black Hills, South Dakota,[4] and Colorado. In all these regions it is found in pegmatites.

Feldspar.—The feldspar utilized in the arts is obtained exclusively from pegmatite veins and deposits formed by magmatic segregation. The principal use is for making pottery, glass, porcelain, enamel brick, and other enamel ware. Potash, soda, and lime feldspars are utilized. Much of the feldspar marketed contains 10 to 20 per cent. of quartz. Mica and iron minerals are objectionable. Orthoclase contains much potash, and experiments have been made to render the potash soluble so that the feldspar may be used for fertilizer, but thus far no process that is commercially successful has been worked out. Feldspar is used also in the manufacture of carborundum and emery wheels, as a flux to bind the abrasive particles together. Small quantities of feldspar are used in making opalescent glass; the varieties most commonly used, according to Bastin, are those rich in soda.

Because the hardness of feldspar is less than that of quartz, it will not so readily scratch glass and consequently there is a demand for quartz-free feldspar for window wash and polishing powder. The production of feldspar in the United States in 1920 was 131,000 short tons, valued at $1,099,000. Nearly all of this was obtained in the New England States and the southern Appalachian region. California also produces feldspar.

[1] Holmes, J. A.: Mica Deposits in the United States. U. S. Geol. Survey *Twentieth Ann. Rept.*, part 6 (continued), pp. 691–707, 1899.

[2] Rice, C. F.: Description of Mica-Mining Company in Grafton County, New Hampshire. *Min. and Sci. Press*, Feb. 23, 1901.

[3] Sterrett, D. B.: Mica Deposits of North Carolina. U. S. Geol. Survey *Bull.* 430, pp. 593–638, 1910.

Pratt, J. H.: The Mining Industry in North Carolina (an annual publication of the N. C. Geol. Survey), 1900–1910.

[4] Sterrett, D. B.: Mica Deposits of South Dakota. U. S. Geol. Survey *Bull.* 380, pp. 382–397, 1906.

The bibliography of feldspar deposits of the United States is extensive. The principal deposits are discussed by Bastin.[1] Citations under "Quartz" (p. 322) refer also to feldspar.

Gems and Precious Stones.—Gems and precious stones are minerals used for ornaments. To be valuable, they should be rare and hard enough to be durable; they should also appeal to the taste for the beautiful. Diamond, emerald, ruby, and sapphire are the more valuable precious stones. The less valuable or "semi-precious" stones include garnet, amethyst, topaz, tourmaline, spodumene, beryl, peridot, turquoise, agate, quartz, chrysocolla—in fact, crystallized specimens of any of the harder minerals may be used for ornaments.[2] The gems and precious stones produced in the United States in 1915 were valued at $170,431.

Diamond is crystallized carbon. Its largest use is as a gem, but its hardness is 10 on the Mohs scale and considerable quantities are used as an abrasive, particularly as diamond dust and for bits of core drills. For core drills the black diamond, carbonado, is in great demand. It has no prominent cleavage and is therefore more durable. Black diamonds sell for $75 to $100 a carat or more. Impure white diamonds used for core drills are much cheaper. They sell at $10 a carat or more, the price depending on grade and durability. Uncut gems are valued at $7 to $12 a carat or more, according to size, color, and appearance. White diamonds are most common. Those with blue tints are highly prized. Yellow diamonds are generally lower priced than white ones. The United States imports diamonds from Africa and from Brazil. The domestic production is small.

Diamonds are mined from plugs of basic igneous rocks (peridotite) in the Kimberly field, Cape Colony; at the Premier mine, near Pretoria, in Transvaal; and in Pike County, Arkansas. They are found in placers in Brazil, India, and at many other places.

[1] Bastin, E. S.: Economic Geology of the Feldspar Deposits of the United States. U. S. Geol. Survey *Bull.* 420, pp. 1–85, 1910.

[2] For data relating to the gems produced in the United States see Kunz, G. F.: "Gems and Precious Stones of North America," 1892, and several papers by D. B. Sterrett in U. S. Geol. Survey *Mineral Resources*, especially the volumes for 1909, part 2, pp. 739–808, 1910, and for 1911, part 2, pp. 1037–1078, 1912.

PROPERTIES OF CERTAIN GEM MINERALS

Gem	Composition	Hardness	Gravity	Color	Crystal system	Principal occurrence
Diamond.....	C	10	3.525	White, etc.	Isometric	Igneous rocks and placers
Emerald.....	$Be_3Al_2(SiO_3)_6$	7.5–8	2.5–2.7	Green	Hexagonal	Pegmatites and placers
Ruby.....	Al_2O_3	9	4	Red	Hexagonal	Pegmatites and placers
Sapphire.....	Al_2O_3	9	4±	Blue	Hexagonal	Igneous rocks pegmatites and placers
Spinel ruby.....	$MgO \cdot Al_2O_3$	8	3.5	Red	Isometric	Igneous rocks and placers
Tourmaline[a].....	Borosilicate	7–7.5	2.98–3.2	Pink, green, yellow, etc.	Trigonal	Pegmatites
Turquoise.....	Hydrated aluminum copper phosphate	6	2.75±	Green, blue		
Topaz.....	$Al_2SiO_4F_2$	8	3.56	Yellow, white, green, etc.	Orthorhombic	Pegmatites, etc., placers
Kunzite.....	$LiAlSi_2O_6$	6.5–7	3.17	Lilac, pink, white	Monoclinic	Pegmatites
Variscite.....	Hydrous aluminum phosphate	4±	?	Green	?	Alteration product?
Peridot.....	Magnesium and iron silicate	6.75	3.3–3.4	Yellow, green, etc.	Orthorhombic	Igneous rocks
Garnet.....	$Mg_3Al_2Si_3O_{12}$ Pyrope	....	3.7	Red, etc.	Isometric	Igneous and sedimentary rocks. Placers
Opal.....	Hydrous silica	....	.....	Red, green, etc.	Amorphous	Lavas, tuffs, etc.

[a] Tourmaline is a complex aluminum borosilicate which may contain magnesium and iron.

The diamonds of South Africa are found in pipes of serpentine, which nearly everywhere is fragmental in character, has a soft chalky consistency, and disintegrates readily on exposure to air. It is of a bluish- or greenish-gray color and is commonly known to the miners as "blue ground." The alteration to serpentine has progressed far, yet many of the original minerals, as well as products of alteration, can be identified. Among the most common minerals besides serpentine are olivine, enstatite, bastite, hypersthene, chrome-diopside, garnet, ilmenite, biotite, vaalite, magnetite, epidote, apatite, calcite, zeolites, and various other minerals in small quantities, such as rutile, chromite, tourmaline, corundum, and kyanite. The serpentine, which now composes most of the mass, has probably been derived from the

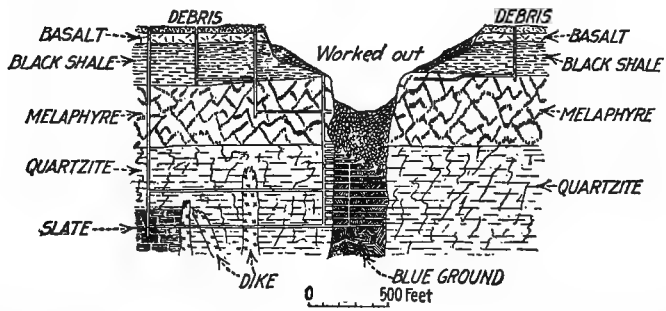


FIG. 183.—Cross-section of Kimberly diamond-bearing peridotite plug. (*After Williams.*)

alteration of olivine and perhaps in part from the alteration of pyroxene. On the surface the "blue ground" assumes a yellow or brown color, due to the oxidation of iron-bearing minerals. There are many pipes in this region that do not contain diamonds.

The Kimberly peridotite plug is shown in Fig. 183. The diameter decreases in depth and has been followed downward over 2,000 feet. The peridotite ("kimberlite") is extensively serpentinized. At the surface it is "yellow;" in depth, "blue ground." It disintegrates after it has been mined and exposed to the elements for a few months. The material is passed over greased tables to which the diamonds adhere. Nearly 1 carat to the ton is recovered. The peridotite plug is intruded into a series of beds among which are carbonaceous shales. Dunn regarded the carbon of the shales as the source of the diamonds, which, according to this view, were formed by the recrystalliza-

tion of carbon from the shales dissolved by the intruding magma.[1] More recent work has shown that the diamonds are original rock-making minerals. Many of the crystals are broken,[2] showing that they had formed (as phenocrysts) before the magma came to rest.

The deposit at the Premier mine, Transvaal,[3] is a pipe of serpentinized peridotite intruding sedimentary rocks. The pipe is situated on a rocky ridge, and the "blue ground," being soft and easily eroded, occupies a sag on the crest of the ridge, while the harder materials form low rocky hills around it. The rocks are mostly quartzites and shales, with intrusive sheets and masses of diabase, felsite, and other igneous rocks, though the rock immediately surrounding the pipe on the surface is mostly felsite. These rocks are classed as the Pretoria series and are of Paleozoic age. Along the beds of streams running from this ridge, diamonds have been extensively mined in the alluvium, having probably come from the erosion of the pipe above.

The Premier pipe is over half a mile long and over a quarter of a mile wide. It is one of several diamond-bearing pipes in this neighborhood, and is the largest yet discovered in Africa. The rock containing the diamonds is oxidized near the surface and converted to a yellowish-brown mass for a depth of 30 to 50 feet, below which the blue color appears. This "blue ground" is a highly serpentinized fragmental material containing numerous pieces of the country rock taken up from the formations through which the "pipe" has passed. In it olivine is still found, together with hypersthene, chrome-diopside, garnet, ilmenite, vaalite, calcite, zeolites, apatite, diamonds, and other minerals. Ilmenite is very abundant. The chrome-diopside is conspicuous by its brilliant green color. Some of the garnets are of a beautiful ruby color.[4]

The diamonds are crystallized octahedrons, but modifications are common. Some of the crystals are distorted, and many broken crystals are found. The diamonds are of white, pink,

[1] DUNN, E. J.: Notes of the Diamond Fields of South Africa. London Geol. Soc. *Quart. Jour.*, vol. 37, pp. 609–612, 1881.

[2] WILLIAMS, G. F.: "Diamond Mines of South Africa," pp. 490, 510, New York, 1902.

[3] PENROSE, R. A. F., JR.: The Premier Diamond Mine, Transvaal, South Africa. *Econ. Geol.*, vol. 2, pp. 275–284, 1907.

[4] *Op. cit.*, pp. 278–279.

yellow, blue, and other colors and are of various sizes. The largest diamond ever found in the mine, which is also the largest diamond ever found in the world, is known as the Cullinan diamond and weighed 3,024¾ carats. It was a broken octahedron about 4 inches long, 2½ inches wide, and 2 inches thick. The blue ground varies considerably in its content of diamonds but averages over half a carat per "load" (about 16 cubic feet).

In the region of the Premier[1] mine the youngest rocks in which the pipes are now found are those of the Pretoria series, though the pipes may once have intersected rocks of the Waterberg series. In the Kimberley[2] region the pipes appear on the surface in the still younger rocks of the Ecca series, which is in the lower part of the Karroo system. At the Monastery mine, in Orange River Colony, the pipe penetrates rocks of the Stormberg series, of the upper part of the Karroo system (Carboniferous?). On account of the marked similarity of composition and mode of occurrence of pipes in widely separated regions, it has been suggested by some that they were all formed at one general epoch. As yet no pipes have been found which show any signs of culminating in a crater, or of any overflow of any kind. Because the rock is soft, they generally occupy depressions.

Much has been written on the origin of the diamonds. They are all found in peridotite (eclogite). Hatch and Corstorphine[2] believe that the eclogite masses were simply parts of a basic magma from which the diamonds and the breccia filling the pipes were derived, and as many of them are broken they must have crystallized before the magma came to rest.

In Pike County, Arkansas,[3] diamonds have been formed in several small peridotite bodies that break through the Trinity (Lower Cretaceous) formation, which consists of clay, sand, gravel, and limestone. The production of Arkansas diamonds is small.

[1] Penrose, R. A. F., Jr.: *Op. cit.*, pp. 280–281.

[2] Hatch and Corstorphine: "Geology of South Africa," p. 298.

[3] Penrose, R. A. F., Jr.: The Premier Diamond Mine, Transvaal, South Africa., *Econ., Geol.*, vol. 2, pp. 275, 1907.

Kunz, G. F., and Washington, H. S.: Diamonds in Arkansas. Am. Inst. Min. Eng. *Trans.*, vol. 39, pp. 169–176, 1908.

Miser, H. D.: New Areas of Diamond-Bearing Peridotite in Arkansas. U. S. Geol. Survey *Bull.* 540, p. 534–546, 1914.

The diamonds of Minas Geraes, Brazil, are obtained from placers. They are associated with fragments of quartzites and schists. Their original source is uncertain.[1]

In southwest Africa,[2] formerly a German province, a considerable diamond industry is developed. Sands along the coast, in a belt about 75 miles long, are found to contain diamonds, most of which are small, about one-sixth of a carat in weight. These stones are highly prized as gems and are set in platinum to produce mass effects. About a million carats a year have been produced. Their genesis is uncertain, but their nearly uniform size suggests that they have been derived from an igneous rock that contained diamond phenocrysts. Some have supposed that the parent rock is now off shore below sea level.

A discussion with bibliography on occurrences and syntheses of diamonds is given by Clarke.[3]

Emerald ($Be_3Al_2(SiO_3)_6$) is a clear green variety of beryl, highly prized as a gem. It is obtained from pegmatite veins[4] and from placers. Some emeralds equal or exceed diamonds in value. Emeralds are imported from India, Ceylon, Siberia, and Brazil. In the United States they are found in pegmatites at several places in New England and in North Carolina. Beryls of colors other than green also are used for gems.

Ruby (red), sapphire (blue), oriental emerald (green), oriental topaz (yellow), and oriental amethyst (purple) are all varieties of gem corundum (Al_2O_3). The colors are probably due to small amounts of various metallic oxides. All are found in placers, where they have probably formed from the waste of igneous rocks and pegmatite dikes. Most of these varieties come from the Orient or from South America. Beautiful blue sapphires are mined from a decomposed dike of lamprophyre at Yogo Gulch,

[1] Derby, O. A.: Brazilian Evidences on the Origin of the Diamond. *Jour. Geol.*, vol. 6, pp. 121–146, 1898.

Branner, J. C.: The Minerals Associated with Diamonds and Carbonates in the State of Bahia, Brazil. *Am. Jour. Sci.*, 4th ser., vol. 31, pp. 480–490, 1911.

[2] Boise, C. W.: The Diamond Fields of German Southwest Africa. *Mining Magazine*, vol. 12, pp. 329–340, 1915.

[3] Clarke, F. W.: The Data of Geochemistry, 3d ed. U. S. Geol. Survey *Bull.* 616, pp. 322–328, 1916.

[4] Sterrett, D. B.: U. S. Geol. Survey *Mineral Resources*, 1911, part 2, pp. 1051–1058, 1912.

Fergus County, Montana.[1] In this dike the sapphire is a rock-making mineral. Near Philipsburg, Mont., sapphires are extensively mined from placers. In the original state they are apparently phenocrysts in a surface lava. Though some of the material is of gem quality, most of it is used for watch jewels and other bearings.

Spinel ($MgO.Al_2O_3$) when red is called "spinel ruby." There are also other shades. Spinel is found in peridotite and in placers which are in part derived from basic rocks.

Tourmaline is a complex hydrous borosilicate which may contain also magnesium and iron. It has a great variety of colors. The dark brown and black tourmalines, which contain iron, are little used as gem material. Gem tourmalines are green, white, red, yellow, etc. Gems are found at Paris, Maine,[2] and at a few other places in New England, and pink tourmaline is obtained from San Diego County, California. Gem tourmalines are found in pegmatite dikes, where they commonly occur as well-defined prismatic crystals lining small cavities. The hardness of tourmaline ranges from 7 to 7.5.

Kunzite (lilac-colored spodumene) occurs with rubellite in pegmatites in southern California. It is a gem of great beauty but is not yet widely used.

Turquoise (hydrated copper-aluminum phosphate; hardness 6) forms small veinlets in rhyolite, granite, and other igneous rocks. It is generally associated with kaolin and other secondary minerals and is probably a product of surface decomposition. It commonly fills small fractures in kaolinized igneous rock. Turquoise is obtained in several localities in Arizona[3] and other States in the arid Southwest.[4] The best gems come from Persia.

[1] ROWE, J. P.: Development of Montana's Sapphire Mines. *Min. World*, vol. 31, pp. 921–923, 1909.

WEED, W. H.: Geology of the Little Belt Mountains, Montana. U. S. Geol. Survey *Twentieth Ann. Rept.*, part 3, pp. 454–460, 1900.

PIRSSON, L. V.: On the Corundum-Bearing Rocks from Yogo Gulch, Montana. *Am. Jour. Sci.*, 4th ser., vol. 4, 1897, p. 421.

STERRETT, D. B.: U. S. Geol. Survey *Mineral Resources*, 1907, part 2, p. 795, 1908.

[2] BASTIN, E. S.: Geology of the Pegmatites and Associated Rocks of Maine. U. S. Geol. Survey *Bull.* 445, pp. 79–93, 1911.

[3] PAIGE, SIDNEY: The Origin of Turquoise in the Burro Mountains, New Mexico. *Econ. Geol.*, vol. 7, pp. 382–392, 1911.

[4] JOHNSON, D. W: School of Mines *Quart.*, vol. 24, p. 493, 1903. ZALINSKY, E. R: *Econ. Geol.*, vol. 2, p. 464, 1907.

Variscite ($AlPO_4 + 2H_2O$) is a green mineral found at a few places in Utah[1] and Nevada. A mixture of variscite matrix with chalcedony and other minerals is called "amatrice." Variscite is probably formed by processes of superficial alteration.

Peridot a clear yellow or greenish-yellow olivine, is found in the Apache and Navajo reservations, Arizona.[2] It is associated with basic igneous rocks, from which it has separated by weathering.

Garnet (pyrope, almandine, and spessartite), is prized as a gem. India is the principal source. The red garnet, rhodolite, of Macon County, North Carolina, is a stone of remarkable beauty. Many red garnets of fine color but of rather small size are found in the Navajo Indian Reservation, Arizona.

Topaz of gem quality is found in the Thomas Range, Utah, where it has evidently accumulated by disintegration of rhyolite in which it is found nearby.[3]

Jade includes two minerals namely, nephrite, an amphibole, $CaMg_3(SiO_3)_4$, and jadeite, $NaAl(SiO_3)_2$, which is related to the pyroxenes. The apple green varieties are greatly prized as gems especially in the Orient.

Lithium Minerals.—Lithium is obtained principally from lepidolite lithium mica, ($KLi[Al(OH,F)_2]Al(SiO_3)_3$), spodumene ($LiAl(SiO_3)_2$), and amblygonite ($Li(AlF)PO_4$). Lithium minerals are exploited in San Diego County, California, and in the Etta and other mines, in the southern Black Hills.[4] Smaller amounts are found at Paris, Maine, and at many other places in New England. Bodies of these minerals of commercial size are practically confined to pegmatite veins (see page 209). The material is normally exported to Germany, where soluble lithium salts are made from the silicates. Lithium salts are used in medicine and in medicinal water.

In 1919 the United States produced 6,372 tons of lithium minerals, valued at $108,370.

[1] PEPPERBERG, L. J.: Variscite near Lucin, Utah. *Min. and Sci. Press*, vol. 103, p. 233, 1911.

[2] PATTON, H. B.: Topaz-bearing Rhyolite of Thomas Range, Utah. Geol. Soc. America *Bull.*, vol. 19, pp. 177–192, 1908.

[3] STERRETT, D. B.: U. S. Geol. Survey *Mineral Resources*, 1908, part 2, pp. 840–842, 1909.

[4] HESS, F. L.: Tin, Tungsten, and Tantalum Deposits of South Dakota. U. S. Geol. Survey *Bull.* 380, pp. 159–161, 1909; U. S. Geol. Survey *Mineral Resources*, 1909, part 2, p. 649, 1910.

Monazite and Xenotime.—Monazite is normally cerium phosphate ($CePO_4$), but rare-earth metals—thorium, praseodymium, lanthanum, neodymium —are generally present in it. Xenotime ($YtPO_4$) is a phosphate of yttria, with rare earths of the cerium group. These minerals are exploited for the rare earths they contain, especially for thorium, which is used for making glowers and mantles for lights. The principal production[1] is derived from the Carolinas, east of the Blue Ridge. The country is an area of gneiss, schist, and granite, cut by various intrusive rocks, including extensive dikes of pegmatite. The monazite is mined mainly from placers, but some is mined from pegmatized gneiss in place, especially where the gneiss has rotted.

Zircon.—Small amounts of zircon (ZrO_2) are present in many igneous rocks. Some pegmatites contain considerable amounts. Zircon resists weathering processes and is concentrated in stream gravels derived from zircon-bearing rocks. In the Carolinas zircon is associated with monazite in gravels. Near Zirconia, Henderson County, North Carolina., zircon is obtained by washing the decomposed croppings of a pegmatite dike.[2] Zircon-bearing pegmatites occur also near Cash in the Wichita Mountains, Oklahoma.[3]

Zircon is used for the manufacture of zirconium compounds, which are used in making glowers for the Nernst electric light.

Graphite.—Graphite is carbon crystallized in the rhombohedral system. Some graphite occurs in very minute particles and is said to be amorphous. Graphite is used for making paints, crucibles, lubricants, lead pencils, polishing powder, etc. Amorphous graphite is preferred for lead pencils, and crystalline graphite for crucibles. Some of the graphitic rock mined carries only a small percentage of graphite and is concentrated mechanically. Material carrying as low as 30 per cent. graphite is ground and used for paint. Graphite is used also as an adulterant for fertilizer, to which it gives the black color which is popularly associated with fertility of soil. As it is insoluble, it

[1] PRATT, J. H and STERRETT, D. B.: Monazite and Monazite Mining in the Carolinas. Am. Inst. Min. Eng. *Trans.*, vol. 40, pp. 313–340, 1909.

[2] STERRETT, D. B.: Monazite and Zircon. U. S. Geol. Survey *Mineral Resources*, 1911, part 2, pp. 1193–1196, 1912.

[3] STERRETT, D. B.: Monazite and Zircon. U. S. Geol. Survey *Mineral Resources*, 1907, part 2, p. 787, 1908.

can not add to fertility, and its use as fertilizer is to be discouraged. The United States produced in 1920 about 9,632,603 pounds of graphite, valued at $1,576,440, and also 4,694 tons valued at $49,758. Most of the importations came from Ceylon, Madagascar and Sonora, Mexico. A large amount of graphite is manufactured from coal at Niagara Falls.

A bibliography of graphite with brief abstracts of the more important papers is given by Bastin.[1]

Graphite occurs in veins, in pegmatites, in igneous rocks, and in metamorphosed rocks. The most productive deposits in the United States are in the region of Crown Point and Ticonderoga, N. Y.,[2] where there are quartz-graphite schists that contain from 3 to 10 per cent. of graphite. The principal deposits, according to Bastin, are metamorphosed sedimentary rocks that contained organic matter. Minerals associated with the graphite include mica, feldspar, pyrite, and zoisite. Graphite is found in pre-Cambrian gneisses and marbles in the Piedmont Plateau region of Pennsylvania. It has been mined at several places and is used principally for the manufacture of crucibles.[3]

Near La Colorado, Sonora, Mexico,[4] Triassic sandstones inclosing coal beds have been metamorphosed by intruding granite and the coal beds are changed to graphite. One bed 10 feet or more thick supplies high-grade amorphous graphite that is greatly prized for making lead pencils. Graphite deposits are found about 7 miles southwest of Raton, New Mexico, where basic intrusions cutting coal beds have converted the coal of the Raton field to graphite[5] (see p. 88).

In Madagascar, off the east coast of Africa, there are large

[1] Bastin, E. S.: U. S. Geol. Survey *Mineral Resources*, 1912, part 2, pp. 1061–1069, 1913.

[2] Bastin, E. S.: Origin of Certain Adirondack Graphite Deposits. *Econ. Geol.*, vol. 5, pp. 134–157, 1910; Graphite. U. S. Geol. Survey *Mineral. Resources*, 1908, part 2, pp. 717–738, 1909 (contains bibliography).

[3] Miller, B. L.: Graphite Deposits of Pennsylvania. Pa. Topographic and Geol. Survey *Rept.* 6, pp. 1–147, 1912.

Hopkins, T. C.: Description of Graphite Deposit of Chester Springs, Chester County, Pa. *Mineral Industry*, vol. 7, p. 383, 1898.

[4] Hess, F. L.: Graphite Mining near La Colorado, Sonora, Mexico. *Eng. Mag.*, vol. 38, p. 36, 1909.

Bastin, E. S.: U. S. Geol. Survey *Mineral Resources*, 1908, part 2, p. 734, 1909.

[5] Lee, W. T.: Graphite. U. S. Geol. Survey *Mineral Resources*, 1908, part 2, p. 733, 1909.

deposist of schist which contain about 5 per cent. of flake graphite. The graphite is concentrated in mills and used extensively in Europe for making crucibles.

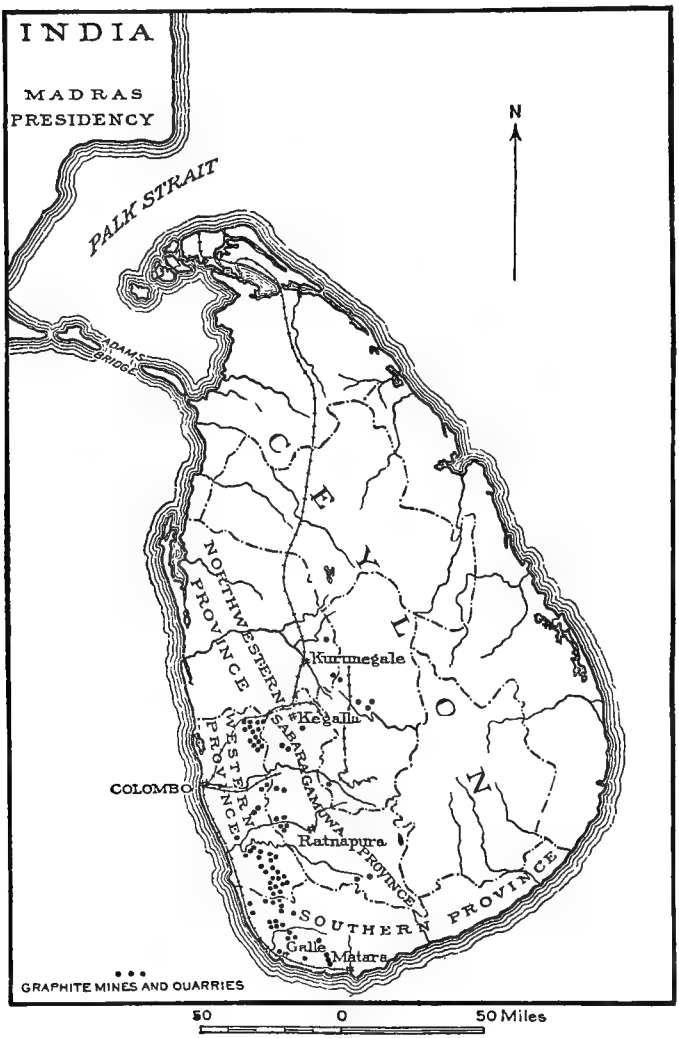


FIG. 184.—Sketch of Ceylon showing position of graphite mines and quarries.

The most productive graphite deposits of the world are those of southwestern Ceylon, which for many years have supplied most

of the graphite used in the United States. Southwestern Ceylon[1] (Fig. 184), is a mountainous area of crystalline rocks consisting of gneisses and "granulites" of acidic and basic types. The graphite deposits, as stated by Bastin, are veins formed presumably at considerable depths. Pyrite and quartz are common associates of the graphite, and in some deposits biotite, orthoclase, pyroxene, apatite, allanite, and rutile occur. The graphite is mined either from open pits or through shafts. Most of the mines are not deeper than 100 feet, though a few are as deep as 400 or 500 feet.

Graphite veins are found about 9 miles southeast of Dillon, Mont.[2] The rocks associated with the graphite deposits are limestone and quartzites, apparently of Paleozoic age, and underlying them quartz schists and slates, which are probably pre-Cambrian. All are intruded by granite and pegmatite, and certain other rocks of contact-metamorphic origin are developed as a result of these intrusions. The graphite is found in metamorphosed sediments, granite, and pegmatite. The principal deposit is a vein about 2 feet wide which consists of an irregular network of graphite veinlets inclosing many sharp-walled schist fragments. The graphite forms about half of the vein material, and the veinlets locally unite to form irregular bunches. When broken between the fingers the graphite separates into splinters which have roughly the shape of a spear-head.

In the Grenville district, near Ottawa, Quebec, limestone is intruded by granite.[3] Near the contact graphite deposits have been formed, probably by contact metamorphism of the limestone. The minerals associated with the graphite are scapolite, pyroxene, biotite, wollastonite, and pyrite. Graphite veins in pegmatites and gneiss are found in Buckingham Township, Quebec.

Graphite is found also in Wisconsin, in the Upper Peninsula of

[1] Bastin, E. S.: The Graphite Deposits of Ceylon. *Econ. Geol.*, vol. 7, pp. 419–443, 1912.

Coomaraswamy, A. K.: On Ceylon Rocks and Graphite. Geol. Soc. London, *Quart. Jour.*, vol. 56, pp. 590 et seq., 1900. The Crystalline Limestones of Ceylon. *Idem*, vol. 58, pp. 399–422, 1902.

[2] Bastin, E. S.: Graphite Deposits of Ceylon. *Econ. Geol.*, vol. 7, p. 435, 1912.

[3] Osann, A.: On the Occurrence of Graphite at Graphite City, Township of Buckingham. Canada Geol. Survey *Twelfth Ann. Rept.*, pp. 066–082, 1899.

Michigan, in the southern Appalachian region, and at other places in the United States.

Quartz and Quartzite.—Quartz is a persistent mineral, occurring in igneous and sedimentary rocks, in ore veins, in pegmatites, and elsewhere. In the West there are many big white barren mineral veins termed "bull quartz" by prospectors. Vein quartz is mined for many purposes. The purer quartzites and also flint and chert are mined in some places. Flint nodules are in demand, especially for tube mills.

Quartz is used[1] for flux, for filling acid towers, and as a refractory material. Various forms of silica are used for making paint, for making filters, for wood filler, for glazing, for making glass, and for mixing with clay to decrease shrinkage of pottery. As an abrasive it is used to make sandpaper, soap, and polishing powder and for the air blast. Rose quartz and some other varieties of silica are used for gems.

Quartz sand is used for various purposes (p. 322). Quartzite, which consists of pure grains of quartz sand cemented with pure silica, can be used for most purposes for which quartz is used. During the war, when shipping was disturbed, a considerable industry was developed in southwestern Minnesota, where pre-Cambrian quartzite was quarried and sold to western metal mines for lining tube mills and as a substitute for flint balls in tube mills. For some purposes the material was found to be as satisfactory as the flint balls that for many years had been imported from England, France, and Norway.

Ganister is an aluminous siliceous rock used for lining furnaces. Commonly it is a metamorphosed clayey sandstone.

[1] Bastin, E. S.: Quartz and Feldspar. U. S. Geol. Survey *Mineral Resources*, 1907, part 2, pp. 843–872, 1908; *Idem.* 1910, part 2, pp. 963–975, 1911.

CHAPTER XII

MAGNESIAN MINERALS

MAGNESIAN MINERALS

Serpentine	$H_4Mg_3Si_2O_9$
Actinolite	$Ca(Mg,Fe)_3(SiO_3)_4$
Anthophyllite	$(Mg,Fe)SiO_3$
Tremolite	$CaMg_3Si_4O_{12}$
Olivine	$(Fe,Mg)_2SiO_4$
Enstatite	$(Fe,Mg)SiO_3$
Magnesite	$MgCO_3$
Talc	$H_2Mg_3Si_4O_{12}$
Meerschaum	$H_4Mg_2Si_3O_{10}$

The chief magnesian minerals are listed above. Olivine and enstatite are found principally in igneous rocks, and tremolite in metamorphic rocks, especially in marbles. Carbonated waters readily alter these and other magnesian minerals, forming serpentine, talc, and magnesite. Commonly, though not invariably, igneous rocks alter to serpentine and metamorphosed sedimentary rocks to talc. It is not known why magnesian silicates acted on by carbonated waters yield such different products, but probably the explanation lies in differences in concentration and in the temperature of the solutions. The problem should lend itself readily to laboratory experiments, but there are few experimental data available. It is well known, however, that basic rocks are altered very readily either by ground water or by the hot solutions that are associated with intrusions.

Asbestos.—Asbestos is a trade term that is applied to minerals that are fibrous and poor conductors of heat and that may be used in making certain products for protection against fire. Most of them are magnesian minerals.[1] Serpentine asbestos or chrysotile, amphibole, anthophyllite, and crocidolite have asbestiform varieties.

Several types of asbestos are recognized—cross-fiber, slip-

[1] DILLER, J. S.: U. S. Geol. Survey *Mineral Resources*, 1908, part 2, pp. 697–706.

fiber, and mass-fiber. The cross-fiber asbestos occurs in veins as much as several inches wide, and the fibers are about normal to the walls of veins (Fig. 185). The slip-fiber occurs on slipping planes, and the fibers are parallel to the planes of movement. Mass-fiber is found as masses not occupying veins or slipping planes, and the threads are arranged haphazard or are radiating.

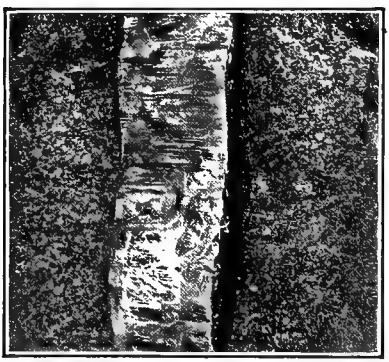


FIG. 185.—Chrysotile asbestos vein in serpentine (Canada).

Most of the cross-fiber asbestos, which is the highest grade, is chrysotile. Much of the mass-fiber is anthophyllite.

As a rule much waste rock is mined with asbestos. The ore is crushed and separated, usually by means of an air blast.

Serpentine asbestos is formed by the alteration of peridotite or certain other rocks. The highest-grade asbestos deposits are veinlets in serpentine. It is believed that they have been formed through the agency of waters that coursed through cracks and fissures, either hot waters soon after the rocks had formed or surface waters later, when the rocks were eroded.

Taber[1] holds that when the cross-fiber asbestos veins form, the mineral, by the force of crystallization, pushes aside the wall rock. Lindgren[2] on the other hand, states that the material of the veins is derived from the serpentine itself and that there is no need for any increase in volume.

Asbestos is used for making fireproof theater curtains, ropes, clothing, etc. When felted it is a good nonconductor of heat and electricity and finds many uses as an insulator. The lower grades are mixed with cement and manufactured into fireproof shingles. These are cheap and for some purposes are superior to tile and slate. Asbestos plaster is used in theaters to deaden noise. Boards are made of asbestos and cement. The demand is increasing, especially for the low-priced materials.

[1] TABER, STEPHEN: The Genesis of Asbestos and Asbestiform Minerals. Am. Inst. Min. Eng. *Trans.*, vol. 57, pp. 62–98, 1917.

[2] LINDGREN, WALDEMAR: "Mineral Deposits," 2d ed., p. 398, 1919.

The most productive deposits of asbestos in North America are at Thetford, Quebec,[1] in a belt of igneous rocks that extends southwestward into northern Vermont[2] (see Fig. 186). The asbestos occurs as cross-fiber veins, closely spaced in a serpentine that has probably been formed by alteration from peridotite. The veinlets, which are from a fraction of an inch to several inches thick, are believed to be alteration products of the igneous rocks

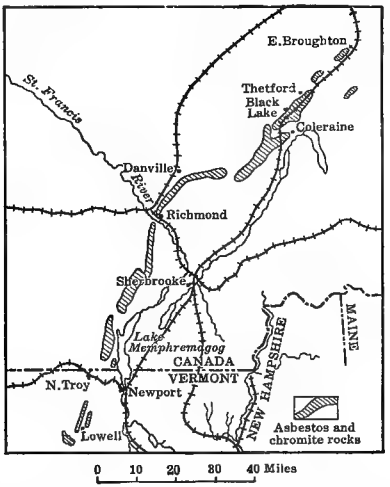


FIG. 186.—Map showing location of asbestos deposits in Canada and in Northern Vermont. (*After Diller, U. S. Geol. Survey.*)

in which they are found. Veins of chrysotile asbestos in serpentine are worked in Orleans and Lamoille counties, Vermont. Near Casper, Wyo.,[3] veins of cross-fiber asbestos occur in serpentine, which also is probably an alteration product of peridotite.

[1] CIRKEL, FRITZ: Chrysotile Asbestos. Its Occurrence, Exploitation, Milling, and Uses, 2d ed. Canada Dept. Mines, Mines Branch, No. 6, 1910.

DRESSER, J. A.: On the Asbestos Deposits of the Eastern Townships of Quebec. *Econ. Geol.*, vol. 4, pp. 130–140, 1909.

MARSTERS, V. F.: Petrography of the Amphibolite, Serpentine, and Associated Asbestos Deposits of Belvedere Mountain, Vermont. Geol. Soc. America *Bull.*, vol. 16, pp. 419–446, 1905.

[2] DILLER, J. S.: The Types and Modes of Occurrence of Asbestos in the United States. Canadian Min. Inst. *Quart. Bull.* No. 13, pp. 45–58, February, 1911.

[3] LAKES, ARTHUR: The Wyoming Asbestos Deposits and Mills. *Min. Sci.*, October 28, 1909.

Arizona is the principal producer of spinning asbestos in the United States. The deposits consist of chrysotile of the cross-fiber type, and the veins occur in cherty limestone, probably of Algonkian age.[1] They yield a product of spinning grade. In the Sierra Anchar, north of Roosevelt, in Gila County, the deposits occur in limestone near diabase sills. Mount Baker is in general capped by thick horizontal sandstones, beneath which extends the asbestos-bearing limestone, intruded and split by the great sill of diabase. The upper surface of the diabase

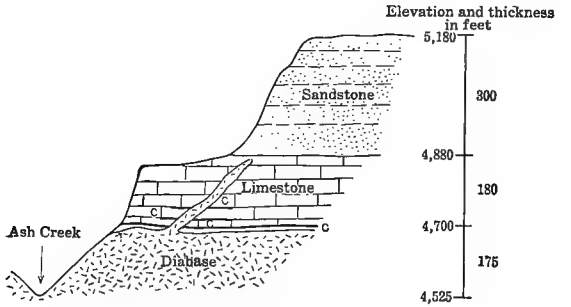


FIG. 187.—Section of eastern slope of Ash Creek, Ariz. *C*, *C*, show locations of cross-fiber asbestos veins. (*After Diller.*)

is irregular. In some places the diabase cuts up through the limestone and completely envelops large fragments of it. At such places the limestone may be fissured and asbestos is likely to be most abundantly developed.

At Ash Creek (Fig. 187) the relations of the rocks are essentially the same. The asbestos veins occur near the diabase, for the most part in the lower portion of the limestone. Their position suggests that the serpentine and asbestos are the result of hydrothermal metamorphic action of the intruding diabase upon the limestone. The asbestos is generally found in greatest abundance in the fissured limestone, where the heated waters that accompanied the intruding diabase magma may have pene-

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DILLER, J. S.: The Types, Modes of Occurrence, and Important Deposits of Asbestos in the United States. U. S. Geol. Survey *Bull.* 470, pp. 512–516, 1911.

RICHARDSON, C. H.: Asbestos in Vermont. Vermont State Geologist *Seventh Rept.*, pp. 315–330, 1910.

[1] DILLER, J. S.: Asbestos in 1917. U. S. Geol. Survey *Mineral Resources*, 1917, part 2, pp. 197–204, 1918.

trated the limestone and converted it into serpentine. The asbestos is said to be most abundant near the surface of the ground, possibly owing to the leaching of the limestone, which is dissolved and removed more readily than asbestos.

Chrysotile asbestos is found 28 miles south of Lander, Wyo.[1] It is in part of spinning grade and occurs in cross-fiber veins along the contact of a dike of pyroxenite or its alteration product, serpentine, and gneissoid rocks or schists. The dike has a width of 400 feet. The serpentine includes fragments or lenses of micaceous schist, and asbestos has been formed locally about these inclusions, as well as on both sides of the serpentine dike. In Idaho, 14 miles southeast of Kamiah, anthophyllite rock is found intruded in mica schist. This rock is quarried and shipped to Spokane, Wash.

Most of the low grade asbestos produced in the United States is mined in Georgia. At Sall Mountain, Ga., according to Diller, anthophyllite asbestos occurs in lenticular masses in gneiss, which is believed to be an altered igneous rock. Near Bedford, Va., there are deposits of mass-fiber presumably derived from basic rocks.

The production of asbestos in the United States is small. In 1920 it amounted to 1,710 short tons, valued at $1,154,000. The value of the annual imports from Canada is about $7,000,000. Large deposits of asbestos are known in Russia, in Italy, and in Cape Colony and Rhodesia, Africa.

Olivine and Serpentine.—Of the magnesian minerals olivine (peridot) has in general no marketable value, though some varieties are used in a small way as gem material. It is, however, an important source of serpentine and other magnesian minerals. It is the principal constituent of peridotites and is present in many other basic rocks that alter to serpentine. It is a valuable protore of iron.

Olivine is one of the most unstable minerals and changes into serpentine with great facility. Peridotites and other basic rocks that in hand specimens appear to be perfectly fresh are almost universally found, when examined microscopically, to be serpentinized along cracks of olivine. As secondary products, both talc and serpentine are formed at very great depths. In California, canyons thousands of feet deep expose serpentine rocks. Either they were formed far below the surface, or altera-

[1] DILLER, J. S.: *Idem.*

tion was more rapid than erosion, which in the surroundings is almost incredible. Lindgren[1] has suggested that olivine has changed to serpentine through the agency of ascending waters associated with igneous intrusives. The alteration of olivine to serpentine involves no great chemical change, as is indicated by the following equation:[2]

$$\underset{\text{Forsterite}}{2Mg_2SiO_4} + CO_2 + 2H_2O = \underset{\text{Serpentine}}{H_4Mg_3Si_2O_9} + \underset{\text{Magnesite}}{MgCO_3}$$

Serpentine develops from olivine and pyroxene rocks that have replaced limestones, and also in ferromagnesian schists. Some serpentine rocks disintegrate readily when piled in dumps. Thus diamond-bearing serpentines in South Africa crumble down in a few months. Serpentine, particularly the green translucent variety, is used for ornamental purposes. The asbestiform varieties of serpentine are mentioned on page 323.

Magnesite.—Magnesite ($MgCO_3$) occurs as a compact amorphous mineral with conchoidal fracture like that of unglazed porcelain. Such magnesite is commonly regarded as an alteration product of olivine, serpentine, enstatite, and other magnesian minerals. The agent is carbonated water, and the manner of formation is indicated above. Magnesite occurs also as a crystalline granular mineral replacing limestone or dolomite. Such deposits in general are found near igneous rocks and are believed to have been formed through the agency of hot solutions that carried magnesium and replaced lime in the sedimentary rock. As noted above, magnesite may be formed when olivine is converted to serpentine. It is formed in veins and fracture zones, filling cavities and replacing serpentine. Commonly associated minerals are chalcedony and quartz. The change from serpentine to magnesite is probably effected through the agency of carbonated water also as indicated by the equation below, serpentine yielding magnesite and silica.

$$H_4Mg_3Si_2O_9 + 3CO_2 = 3MgCO_3 + 2H_2O + 2SiO_2$$

[1] Lindgren, Waldemar: "Mineral Deposits," p. 343, New York, 1913.
Benson, W. N.: The Origin of Serpentine, a Historical and Comparative Study. *Am. Jour. Sci.*, 4th ser., vol. 46, pp. 693–731, 1918.

[2] For simplicity I have used forsterite, the magnesium olivine, free from iron. Fayalite (Fe_2SiO_4) is the corresponding iron olivine. Both species are comparatively rare. Common olivine generally contains both iron and magnesium.

Considerable deposits are found in California,[1] especially in the Coast Range. Almost if not quite invariably the magnesite is associated with serpentine.

At the Winchester mine,[2] in Riverside County, California (Fig. 188), magnesite is mined from a deeply decomposed ser-

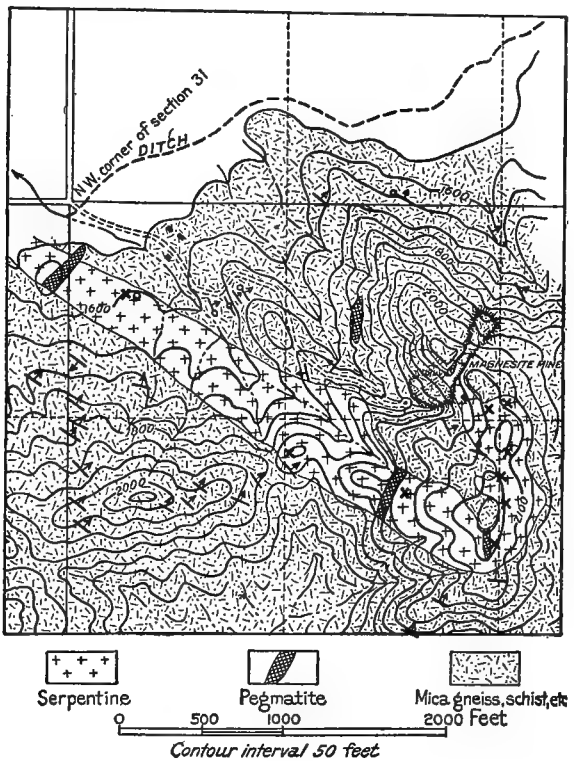


FIG. 188.—Topographic and geologic map of the magnesite deposit at Winchester, Riverside County, Calif. (*After Gale, U. S. Geol. Survey.*)

pentine rock which is intruded in crystalline schists. The serpentine is cut by an intricate network of magnesite veins.[3]

[1] HESS, F. L.: The Magnesite Deposits of California. U. S. Geol. Survey *Bull.* 355, pp. 1–67, 1908.

GALE, H. S.: Late Developments of Magnesite Deposits in California and Nevada. U. S. Geol. Survey *Bull.* 540, pp. 483–520, 1912.

[2] GALE, H. S.: Magnesite. U. S. Geol. Survey *Mineral Resources*, 1911; part 2, pp. 1122–1124, 1912.

[3] RIES, HEINRICH: "Economic Geology," Fig. 1, pl. 35, p. 356, Wiley & Son's New York, 1916.

Near Porterville, Cal.,[1] magnesite is found as small veins in serpentine, which near the deposits is intruded by granite. Magnesite veins in serpentine are mined at Euboea, Greece.

Near Chewelah, Stevens County, Washington,[2] deposits of magnesite are found replacing dolomite near igneous intrusions. These deposits, which are much more extensive than those of California, contain magnesite of the granular type. They supply a large part of the American product.

The largest magnesite deposits known are at Veitsch,[3] in Styria, Austria. These deposits also replace dolomite near igneous intrusions.[4]

In Grenville Township, Quebec,[5] magnesite is mined from deposits in which it is associated with serpentine, dolomite, and diopside. The magnesite is much deformed by movement.

Magnesite is used principally for making refractory brick for smelting, for packing steam pipes, and in the manufacture of paper, carbon dioxide, oxychloride cement, medicines, etc. Magnesite gives off carbon dioxide at a comparatively low temperature and is preferred to other carbonates for making gas for carbonating waters. Calcined magnesite is the crude magnesite burned at a high temperature (about 1200°C.); ferromagnesite is magnesite mixed with iron ore and burned. The crude magnesite, crushed very fine, is mixed with ground iron ore and burned in kilns; the powdered product is ground and made into bricks or sold for use in furnace bottoms. The United States produced 303,767 short tons of magnesite in 1920, valued crude, at $2,748,150.

Talc.—Tremolite, enstatite, and other magnesian minerals break down readily, forming talc. The reactions, according to Clarke,[6] are as follows:

$$CaMg_3Si_4O_{12} + H_2O + CO_2 = \underset{\text{Talc}}{H_2Mg_3Si_4O_{12}} + CaCO_3$$

$$Mg_4Si_4O_{12} + H_2O + CO_2 = \underset{\text{Talc}}{H_2Mg_3Si_4O_{12}} + MgCO_3$$

[1] HESS, F. L.: The Magnesite Deposits of California. U. S. Geol. Survey *Bull.* 355, pp. 1–67, 1908.

[2] DOLMAN, C. D.: Magnesite: Its Geologic Products and Their Uses. Am. Inst. Min. Eng. *Trans.*, vol. 62, p. 15, 1920.

[3] REDLICH, K. A.: Die Genese der Pinolitmagnesite, Siderite und Ankerite der Ostalpen *Min. pet. Mitt.*, vol. 26, pp. 499–505, 1907.

[4] REDLICH, K. A.: Genese der Kristallinen Magnesite. *Zeitschr. prakt. Geologie*, vol. 21, pp. 90–101, 1913.

[5] WILSON, M. E.: Magnesite Deposits of Grenville District, Argenteuil County, Quebec. Can. Geol. Survey *Mem.* 98, 1917.

[6] CLARKE, F. W.: The Data of Geochemistry, 3d ed. U. S. Geol. Survey *Bull.* 616, p. 415, 1916.

Compact and impure talc is called soapstone. In many places talc is formed by the alteration of tremolite-bearing limestone or from basic igneous rocks. Talc is found in schists or dynamically

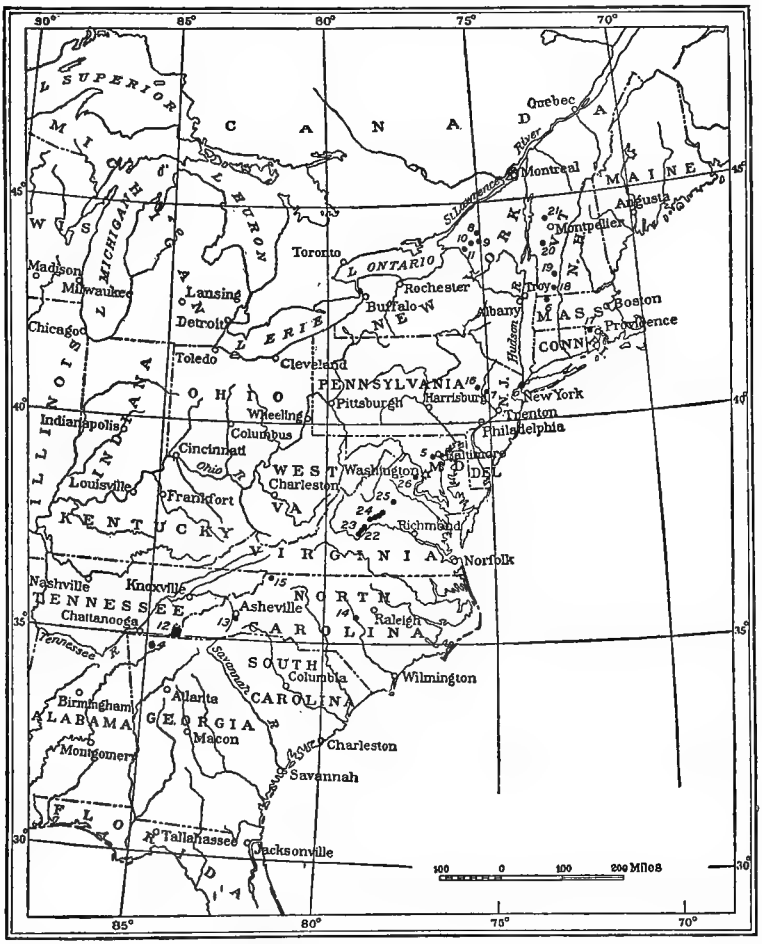


FIG. 189.—Map showing distribution of talc and soapstone mines in eastern United States. (*After Diller, U. S. Geol. Survey.*)

4. Chatsworth, Ga.
5. Marriottsville and Bald Friar, Md.
6. Zoar and Rowe, Mass.
7. Phillipsburg, N. J.
8. Talcville, N. Y.
9. Fullerville, N. Y.
10. Fowler, N. Y.
11. Natural Bridge, N. Y.
12. Kinsey, N. C.
13. Beta, N. C.
14. Glendon, N. C.
15. Piney Creek, N. C.
16. Easton, Pa.
17. Manville, R. I.
18. Windham, Vt.
19. Perkinsville, Vt.
20. Stockbridge, Vt.
21. Waterbury, Vt.
    Johnson, Vt.
22. Asbestine, Va.
23. Shipman, Va.
    Elmington, Va.
24. Schuyler, Va.
    Damon, Va.
    Alberene, Va.
25. Verdierville, Va.
26. Clifton, Va.
    Wiehle, Va.

metamorphosed rocks.[1] Dynamic metamorphism is not necessary for its development, however, as it is found also in rocks that are not highly schistose.

Talc and soapstone are used as refractories, in laboratory tables and tubs, gas burners, electric insulators, crayons, etc. Ground to powder they are used in making paper, paint, toilet powder, and dynamite.

The use of talc is increasing. Most of it is ground and sold in the powdered form, but the large blocks are sawed and sold as soapstone. It is extensively used because it is softer than other stone and can be cheaply shaped. The United States in 1920 produced 222,724 tons of talc and soapstone, valued at $3,052,038.

The deposits of talc and soapstone are found in the Appalachian States (Fig. 189) and on the west coast. Deposits near Gouverneur, N. Y.,[2] yield the larger part of the ground talc. The product is used largely as a paper filler. The layers of talc are found in schistose layers of enstatite and tremolite which are in a crystalline limestone. In Swain County, southwestern North Carolina,[3] talc is found at many places where it forms lenticular bodies in a white marble. The marble contains abundant tremolite, from which the talc is evidently derived.

Most of the soapstone is produced in Virginia. The deposits are layers 100 feet or more thick, interbedded with quartzitic schists.[4]

In Canada talc is mined in Madoc Township, Hastings County, Ontario, where, according to Dresser,[5] it occurs in a limestone of the Grenville series, near intruding granite.

Talc is mined on the north slope of the Pyrenees in France and in Styria, Austria.

Meerschaum.—Meerschaum is probably derived from serpentine and from impure dolomites. Its uses for smokers' articles are well known. Most of it is imported from Asia Minor. In New Mexico it forms veins and balls in cherty limestone.[6]

[1] Diller, J. S.: U. S. Geol. Survey *Mineral Resources*, 1908, part 2, pp. 869–878, 1909.

[2] Smythe, C. H., Jr.: The Genesis of the Talc Deposits of St. Lawrence County, New York. School of Mines *Quart.*, vol. 17, pp. 333–341, 1896.

[3] Pratt, J. H.: N. C. Geol. Survey, *Econ. Paper* 3, pp. 1–29, 1900.

[4] Watson, T. L.: "Mineral Resources of Virginia," p. 293, 1907.

[5] Dresser, J. A.: Mineral Deposits of the Serpentine Belt of Southern Quebec. Can. Min. Inst. *Trans*, vol. 12, pp. 163–183, 1910.

[6] Sterrett, D. B.: Meerschaum in New Mexico. U. S. Geol. Survey *Bull.* 340, pp. 466–473, 1908.

CHAPTER XIII

PHOSPHATES

Each year plants subtract from soils appreciable amounts of mineral matter. Unless this is replenished, the productivity of the soil will ultimately be impaired. For some crops, especially for grains, lime, potash, phosphorus, and nitrates are necessary. Any one or all of these may be insufficient in the soil. Lime is supplied as limestone, marl, or gypsum. Limestone and marl are especially useful when it is desired to correct acid soils. The limestone is generally ground to fine dust and sometimes it is calcined and slaked before grinding. Gypsum is sold in the raw state finely ground. When used for fertilizer, it is called land plaster. Potash is supplied as the sulphate (kainite), as chloride and as niter (potassium nitrate), though niter is too expensive for general use. Greensand marl, which contains some potash in the mineral glauconite (a hydrous iron and potassium silicate), is also used as a fertilizer. The potash in glauconite is less readily available, however, for it dissolves but slowly. Phosphorus is supplied by bone phosphate, rock phosphate, apatite, and wavellite; all are generally treated with sulphuric acid to make the phosphate more soluble. Finely ground phosphate rock is applied to soils in the raw state, but as it is slowly soluble a longer time must elapse before the investment yields returns. Mineral phosphates[1] compete with bone meal and fish waste, which contain calcium phosphate. In Europe the phosphates obtained by the basic open-hearth process of making steel are used for fertilizer.

Nitrates are formed in soils by certain bacteria working in conjunction with leguminous plants; deficiency in nitrates, therefore, may be corrected by suitable rotation of crops. Some commercial fertilizers contain sodium or potassium nitrates or ammonia salts.

Guano, used for fertilizer, is the excrement of animals, chiefly of birds and bats. Some islands of the sea are thickly covered with a mantle of guano, and formerly large quantities of this

[1] Penrose, R. A. F., Jr.: Nature and Origin of Deposits of Phosphate of Lime. U. S. Geol. Survey *Bull.* 46, pp. 1–143, 1888.

material were imported, especially from Peru. In Texas bat guano has been recovered from caves.[1]

Sulphuric acid is extensively used to convert rock phosphate and bones into the more soluble superphosphate. Thus there is a close relation between the acid and phosphate fertilizer industries, and many fertilizer companies operate acid plants.

Phosphate rock is a noncrystalline material, principally lime phosphate; it contains as a rule 25 to 35 per cent. P_2O_5, and about 40 to 50 per cent. CaO. Other radicles commonly present are SiO_2, Al_2O_3, Fe_2O_3, and $CaCO_3$. Apatite $[(CaF)\ Ca_4(PO_4)_3]$ contains 42.3 per cent. P_2O_5. Wavellite has the formula $4AlPO_4.2Al(OH)_3 + 9H_2O$, which corresponds to 35.2 per cent. P_2O_5. Of these products phosphate rock yields much the greatest quantity of fertilizer. In 1920 the United States produced 4,103,982 tons of phosphate rock, valued at $25,079,972 nearly all of which was from Florida, Tennessee, and South Carolina. A little apatite is produced as a by-product of the magnetic separation of iron ores in the Adirondack region, New York.

Phosphate rock occurs in sedimentary beds or as surface concentrations formed by the weathering of such beds. It is commonly associated with marine limestone and is generally of marine origin. Its color is white, gray, brown, blue, or black, depending on impurities. Some of it is made up of numerous shells or fragments of shells. The pisolitic or oolitic texture is very common.

Of the origin of phosphate rock there is yet much to be learned. Some is doubtless formed by the bodies and waste of marine animals. Some is probably precipitated directly from sea water. Richards and Mansfield[2] regard the oolitic texture of Idaho phosphate as original. Shells of animals that normally have lime carbonate shells are found to be made up of mixtures of lime carbonate and lime phosphate.

The textural features of some phosphate rocks are similar to those found in Alabama hematites (p. 399). The beds of phosphate and hematite are likewise very extensive. Doubtless

[1] Phillips, W. B.: Bat Guano Caves. *Mines and Minerals*, vol. 21, p. 440, 1901.

[2] Richards, R. W., and Mansfield, G. R.: Preliminary Report on a Portion of the Idaho Phosphate Reserve. U. S. Geol. Survey *Bull.* 470, p. 371, 1911.

Blackwelder, Eliot: Origin of Rocky Mountain Phosphate Deposits. Geol. Soc. America *Bull.*, vol. 26, p. 100, 1916.

the origin of both is closely similar, and probably some phosphate is precipitated directly from sea water and other phosphate replaces calcareous material on the sea bottom.

Where phosphatic limestone weathers lime carbonate is removed more rapidly than lime phosphate. Some deposits form residual masses due to surface concentration. The western deposits are generally richer at the outcrop than in depth, owing to the removal of lime carbonate. There are many beds in the West, however, that are of high grade in what appears to be the original concentration. Here also, in their enrichment these deposits show a similarity to the Clinton type of iron ores.

Apatite is not important as a source of phosphate. In the Adirondacks it occurs with magnetite in deposits formed by magmatic segregation. The production from these deposits is small. In Ontario and Quebec, notably at Templeton, Quebec,[1] considerable deposits of apatite are found with pyroxene, mica, and calcite in what appear to be contact-metamorphic or nearly related deposits. The Canadian apatites have been almost driven from the market by the higher-grade phosphate rock, and now the deposits are worked principally for mica.

Apatite is the most abundant rock-making mineral that contains phosphorus and doubtless is the chief original source of the element. Clarke[2] cites many analyses of river water which carry from a trace to 1.6 per cent. PO_4. Sea water, on the other hand, contains only traces of phosphorus. It is removed to form the bones of fishes and other aquatic vertebrates and is precipitated in phosphatic nodules that are found on the sea bottom. It is probably precipitated also by the metasomatic replacement of lime carbonate shells.

Phosphate rock is readily decomposed by sulphuric acid, and in sulphide deposits phosphate is migratory. In normal ground water, however, the lime phosphate is not very soluble. The use of finely ground phosphate for fertilizer is not popular because as noted the phosphate dissolves very slowly. In mountainous regions, where erosion is fairly rapid, phosphate rock is not

[1] Penrose, R. A. F., Jr.: Nature and Origin of Deposits of Phosphate of Lime. U. S. Geol. Survey *Bull.* 46, pp. 34–39, 1888.

Cirkel, Fritz: Mica; Its Occurrence, Exploitation, and Uses. Canada Dept. Mines, Mines Branch, pp. 1–148, 1905.

[2] Clarke, F. W.: The Data of Geochemistry, 3d ed. U. S. Geol. Survey *Bull.* 616, pp. 75–106, 1916.

dissolved and reprecipitated to any great extent but is enriched by the removal of calcite, which is commonly present in the phosphate rock. In flat countries, where erosion is slower, especially on peneplaned surfaces, phosphate is much concentrated at places by the removal of calcite. Some phosphate goes into solution also and is precipitated in depth by calcite. The enrichment is thus accomplished, and in areas long exposed to chemical denudation this process may result in considerable concentration. Solution and reprecipitation of phosphate have resulted in concentration in Florida, South Carolina, and Tennessee.

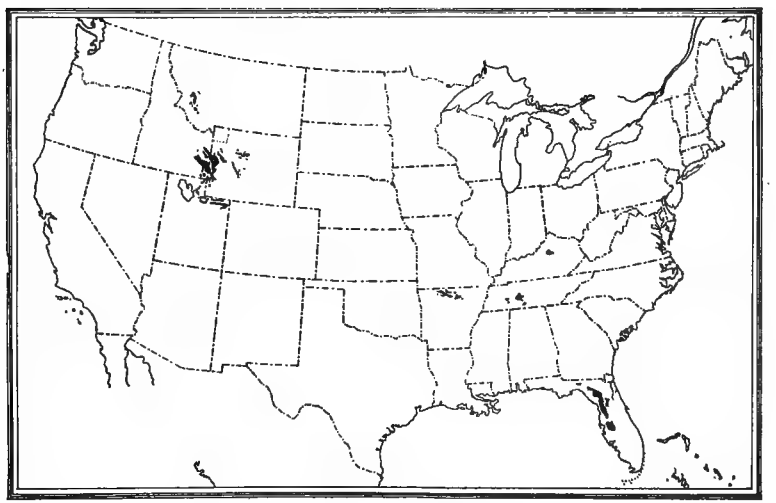


FIG. 190.—Map of United States showing location of principal phosphate deposits. (*Based on map by Phalen.*)

Florida.—The deposits of phosphates in the United States are shown by Fig. 190. Although the Florida deposits are not the largest, they are the most productive in the United States or in the world. These deposits supply a large part of the domestic demand and much phosphate rock for export to Europe. They occur in the northwestern part of the peninsula, and the productive belt lies parallel to the shore. The rock section[1] is as follows:

[1] SELLARDS, E. H.: Origin of the Hard Rock Phosphate Deposits of Florida. Fla. Geol. Survey *Fifth Ann. Rept.*, pp. 23–80, 1913; The Pebble Phosphates of Florida. Fla. Geol. Survey *Seventh Ann. Rept.*, pp. 25–116, 1915.

Pleistocene.—Steam gravels and alluvium; includes river gravel phosphate, of which the Peace Creek beds are best known.

Pliocene.[1]—Bone Valley formation. Lower part, which rests unconformably on the Oligocene, is made up of phosphatic sands and pebbles of phosphate. It is the "land pebble phosphate" and contains also bones and other fossils. Maximum thickness 30 feet or more.

Oligocene.—Alum Bluff formation: Sand, clay, and marl; contains throughout more or less phosphatic material; forms the bedrock of the phosphate mines and is the parent rock from which the pebble phosphates were derived.

Vicksburg Formation.—Yellow limestone and green clay, flint beds and nodules.

Eocene.—Ocala formation: Marine limestones.

The Alum Bluff formation[2] is believed to be the parent rock from which all the phosphate deposits were derived. At the base of the Alum Bluff, resting in pits and solution cavities at the top of the Vicksburg limestone, is found the "hard rock phosphate." This material contains fragments of lime phosphate embedded in a matrix of the phosphate. Part of it has been leached from the Alum Bluff, which is or, before erosion, was above the Vicksburg, and has been reprecipitated on contact with calcium carbonate. Some mechanical concentration has taken place also. The plate rock phosphate is a variety of the hard rock, composed of plates and probably formed by disintegrating hard rock.

The "land pebble" deposits of the Bone Valley formation, which are the most productive, have been redeposited in an encroaching sea that washed over and stratified the detrital and residual phosphate material of the Alum Bluff.

South Carolina.—In South Carolina phosphate deposits are found near Charleston (Fig. 190), in Tertiary and Recent strata. The principal deposits are in the Edisto marl,[3] of Miocene age, which rests unconformably on the Cooper (Eocene or Oligocene). According to Rogers, the phosphate in the Edisto is a reconcentrated residuary product of the Copper marl, reworked and reconcentrated by solution. The bed where rich is 1 to 2½ feet thick. Its average composition is about 58 per cent. tricalcium phosphate. The river deposits are concentrations in streams, probably formed during Edisto time and later.

[1] Possibly late Miocene. SELLARDS, *Op. cit. Seventh Ann. Rept.*, p. 41.

[2] MATSON, G. C.: The Phosphates of Florida. U. S. Geol. Survey *Bull.* 604, pp. 1–101, 1915.

[3] ROGERS, G. S.: The Phosphate Deposits of South Carolina. U. S. Geol. Survey *Bull.* 580, pp. 183–220, 1915.

Tennessee.—In Tennessee[1] brown phosphate rock is found in Ordovician limestone, blue or black phosphate rock in Devonian and Mississippian rocks, and white phosphate rock in Silurian limestones.

The brown phosphates are residual deposits formed from different beds of phosphatic limestone by the action of surface waters charged with carbonic and other organic acids. The calcium carbonate has been more or less completely removed while additional phosphate derived from other beds or other parts of the same bed has been deposited, most of the clay and iron, together with the less soluble calcium phosphate, being left behind.

The blue phosphates consist of several varieties of black or blue bedded phosphates which usually form the basal member of the Chattanooga shale, and of a nodular or "kidney" phosphate which occurs in a thin bed of greensand shale lying immediately above the black shale and constituting the basal member of the Mississippian of that region. These beds are essentially unaffected by weathering.[2] White phosphate is found in cavities in the Decatur limestone, of the Silurian.

Other Eastern States.—In Kentucky[3] the phosphate rock is a residual deposit from Ordovician phosphatic limestones. Phosphate rock is found also in Alabama[4] and Arkansas.[5]

Wavellite ($4AlPO_4.2Al(OH)_3.9H_2O$) has been mined for phosphorus near Mount Holly Springs, Pa. There, as stated by Stose,[6] it forms nodules and masses in white clay in surface

[1] HAYES, C. W., and ULRICH, E. O.: U. S. Geol. *Atlas*, Columbia Folio, (No. 95), U. S. Geol. Survey, 1903.

WAGGAMAN, W. H.: A report on the Natural Phosphates of Tennessee, Kentucky, and Arkansas. U. S. Bureau of Soils *Bull.* 81, 1912.

JENKINS, O. P.: Phosphate and Dolomites of Johnson County, Tennessee. Tenn. Geol. Survey, "Resources of Tennessee," vol. 6, pp. 51–106, 1916.

[2] MANSFIELD, G. R.: The Phosphate Resources of the United States. Second Pan American Scientific Congress, vol. 8, pp. 729–765, 1917.

[3] FOERSTE, A. F.: The Phosphate Deposits in the Upper Trenton Limestones of Central Kentucky. Ky. Geol. Survey *4th. ser.*, vol. 1, part 1, pp. 391–439, 1913.

[4] SMITH, E. A., and MCCALLEY, H.: Index to Mineral Resources of Alabama, pp. 63–65, Ala. Geol. Survey, 1904.

[5] BRANNER, J. C.: The Phosphate Deposits of Arkansas. Am. Inst. Min. Eng. *Trans.*, vol. 26, pp. 580–598, 1896.

[6] STOSE, G. W.: Phosphorus Ore at Mount Holly Springs, Pa. U. S. Geol. Survey *Bull.* 315, pp. 475–483, 1907.

sands with ores of manganese and limonite, and it is probably a disintegration product of older phosphatic beds.

Western States.—The deposits of phosphate rock in Utah Idaho, Wyoming, and Montana[1] are the most extensive known. These deposits, although of high grade, are not now worked except on a small scale. They will probably be worked extensively within a few decades, when western soils will require fertilizers, or as soon as prices or freight rates permit shipment. The deposits are sedimentary beds associated with limestones, sandstones, and shales and are but little altered by surface leaching. They occur in the upper Mississippian and the Permian. The higher-grade beds are in the Permian. Many of the beds are 3 to 8 feet or more thick. The deposits are believed to be original sedimentary rocks; they are expected to extend to great depths. Similar deposits have been sought for in western Canada.[2]

[1] BLACKWELDER, ELIOT: Phosphate Deposits East of Ogden, Utah. U. S. Geol. Survey *Bull.* 430, pp. 536–551, 1910.

GALE, H. S., and RICHARDS, R. W.: U. S. Geol. Survey *Bull.* 430, pp. 457–535, 1910.

SCHULTZ, A. R.: A Geological Reconnaissance of the Uinta Mountains, in Northern Utah, with Special Reference to Phosphate. U. S. Geol. Survey *Bull.* 690, pp. 31–94, 1919.

GALE, H. S., and RICHARDS, R. W.: Preliminary Report on the Phosphatic Deposits in Southeastern Idaho and Adjacent Parts of Wyoming and Utah. U. S. Geol. Survey *Bull.* 430, pp. 457–535, 1909.

MANSFIELD, G. R.: A Reconnaissance for Phosphate in the Salt River Range, Wyo. U. S. Geol. Survey *Bull.* 620, pp. 331–349.

RICHARDS, R. W., and MANSFIELD, G. R.: The Phosphate Deposits Northeast of Georgetown, Idaho. U. S. Geol. Survey *Bull.* 577, pp. 1–76, 1914.

[2] DE SCHMID, HUGH S.: A Reconnaissance for Phosphate in the Rocky Mountains. Canada Dept. Mines, Mines Branch, *Summary Rept.*, 1916, pp. 22–35, 1917.

CHAPTER XIV

SALINES, GYPSUM, NITRATES AND IODINE

Salt.—Salt (NaCl) is widely distributed. It is the most abundant compound dissolved in sea water, and it is abundant also in saline lakes and in beds in the earth. The salt[1] of commerce is obtained from beds of rock salt that are associated with other sedimentary rocks and from natural brines or bitterns.

Some of that obtained from beds is mined in the lump form, but much of it is dissolved by pumping hot water into the beds and subsequently pumping out the water and the dissolved salt. The salt in a pure state is separated from the solution by evaporation. Much rock salt mined in the crude state is refined by dissolving it in water and subsequently evaporating the solution. Salt is obtained from natural brines of many different sources, among them the sea, inland lakes, salt springs, and the salt water that fills the openings in sandstones that were buried in past geologic ages.

The uses of salt are well known. It is of service principally for domestic purposes, as a preservative for packing meats and other substances, and for making other sodium and chlorine compounds.

When sea water is evaporated, its mineral salts are precipitated, the least soluble first. The order of precipitation depends not only on the solubility of the salts in pure water, but also upon concentration, temperature, pressure, and other salts dissolved in the water. If certain minor constituents such as iron, manganese, and phosphorus are omitted the composition of the ocean may be stated as follows:[2]

[1] Grabau A. W.: Geology of the Non-Metallic Minerals other than Silicates, vol. 1, "Principals of Salt Deposition" pp. 1–434, New York, 1920.

Harris, G. D., Maury, C. J., and Reinecke, L.: Rock Salt, its Origin, Geological Occurrences, and Economic Importance in the State of Louisiana, together with Brief Notes and References to All Known Salt Deposits and Industries of the World. La. Geol. Survey *Bull.* 7, pp. 259, 1908.

[2] Clarke, F. W.: The Data of Geochemistry, 3d ed. U. S. Geol. Survey *Bull.* 616, p. 23, 1916.

Composition of oceanic salts		Composition of ocean	
$NaCl$	77.76	O	85.79
$MgCl_2$	10.88	H	10.67
$MgSO_4$	4.74	Cl	2.07
$CaSO_4$	3.60	Na	1.14
K_2SO_4	2.46	Mg	0.14
$MgBr_2$	0.22	Ca	0.05
$CaCO_3$	0.34	K	0.04
		S	0.09
	100.00	Br	0.008
		C	0.002
			100.000

If sea water is evaporated to dryness, the salts will separate approximately in the following order: Calcium carbonate with a little iron oxide, calcium sulphate, sodium chloride, magnesium sulphate and magnesium chloride, sodium bromide, and potassium chloride and sulphate. At some stages,[1] two or more of the salts are precipitated simultaneously. If an arm of the sea is shut off from the main body, its water evaporated, and the resulting salts covered by clay or some other impermeable bed, the saline deposit will be preserved. Such is probably the origin of the famous deposits of Stassfurt, Germany.[2] There the beds from the bottom up are (1) anhydrite and gypsum, (2) rock salt and anhydrite, (3) polyhalite (hydrated lime-magnesium-potassium sulphate), (4) kieserite ($MgSO_4.H_2O$), (5) carnallite ($KMgCl_3.6H_2O$), locally overlain by sylvite (KCl). Above the potash salts is a bed of clay, and above that more anhydrite and salt, indicating probably a later precipitation from the sea water. Above the salt deposits are thick beds of sandstone. The deposits were first worked for salt alone but have more recently furnished the world's chief supply of potash minerals that are extensively used for fertilizer.

Some salt beds are 1,000 feet or more thick. The volume of the salts precipitated from sea water is less than 2 per cent. of the water. For 1,000 feet of salt to be deposited by precipitation over the floor of a basin it is necessary to assume a volume of salt water having the concentration of the ocean equal to a depth of 50,000 feet over the basin. So deep a basin appears improbable.

[1] Usiglio, J.: *Annales chim. phys.*, 3d ser., vol. 27, pp. 92, 172, 1849.

[2] For a clear discussion of this subject with numerous references see Clarke, F. W.: *Op. cit.*, pp. 221–228.

Even if we assume a shrinking lake or inland sea, which would of course result in concentrating the salts over a smaller area, the hypothesis still appears improbable, for the basin required would be deeper than any existing today.

To account for the great thicknesses of some salt beds, Ochsenius proposed the "bar" hypothesis, in which it is supposed that sea water passes over a bar into a large basin near shore, and that evaporation is balanced by a flow of water from the sea over the bar. When evaporation reaches a certain stage precipitation begins. Concentration may go only far enough to precipitate gypsum or only far enough to precipitate gypsum and salt, and the more soluble salts may be carried by reversed movement of water back to the sea. If a bar finally rises and shuts in the bittern or magnesium and potassium solutions from which salt and gypsum have been precipitated, then the sulphates and chlorides of magnesium and potassium will be precipitated above the sodium chloride. This hypothesis of course demands a nice adjustment of conditions, which is probably rarely met; it is noteworthy, however, that the potash salts are not associated with all deposits of salt and gypsum. In fact, thus far they have not been developed in great abundance except in Europe.

In the United States salt is obtained from beds of Paleozoic and later age and from basins where evaporation is now going on. At most places it is obtained by the evaporation of brines pumped from the saline rocks. The production of salt in 1918 was 7,238,744 short tons, valued at $26,940,361. In New York salt is obtained by pumping brines from the Salina (Silurian) beds, where, with gypsum, it occurs as lenses in shales.[1]

In Michigan brines are obtained from Mississippian sandstones in Saginaw Valley. Water is pumped into the sands and pumped out with dissolved salt. The brines from the upper beds of the Marshall formation, are rich in bromine and supply most of the bromine output of the United States. Much of the salt is utilized in manufacturing sodium carbonate.[2]

In Ohio[3] salt is obtained from brines from the Mississippian

[1] Merrill, F. J. H.: N. Y. State Mus. *Bull.* 11, 1893.

[2] Cook, C. W.: The Brine and Salt Deposits of Michigan. Mich. Geol. and Biol. Survey, Geol. ser. 12, pp. 1–188, 1914.

[3] Bownocker, J. A.: Salt Deposits and the Salt Industry in Ohio. Ohio Geol. Survey, 4th ser., vol. 8, pp. 1–42, 1906.

and also from the Salina beds. In Kansas salt is mined from Permian rocks by means of shafts and obtained from salt springs. In the Western States salt is obtained from undrained basins where it is forming today. At Saline Valley, Inyo County, California,[1] a deposit of salt occupies about a square mile in a deep basin. This pure-white salt (98.52 per cent. NaCl) requires no refining.

Salt is evaporated from sea water on San Francisco Bay, California,[2] and from the waters of Salt Lake, Utah.

On the Gulf coast in Louisiana and Texas there are some of the most remarkable salt deposits in the world. Shafts and bore holes sunk in low knobs or domes, some of which project as low islands above marshes, encounter bodies of salt 2,000 feet thick or more. The associated rocks are Tertiary and Quaternary sands, limestones, and clays. The beds have quaquaversal dips away from the salt deposits. Some have thought that the salt deposits were formed by precipitation along fissures by ascending hot solutions, and Harris[3] believes that the force of crystallization has bowed up the rocks into the characteristic domes. That such a force should be so potent seems incredible, yet the "bar" hypothesis seems inadequate to account for these unusual deposits.

Limestone beds are found above the salt beds in several of the domes. At Spindletop, Tex.,[4] and in some other salt domes of the coast region, petroleum is associated with the salt, and gypsum and sulphur also are found in some of the deposits.

Many of the salt domes occur in lines. It is a growing belief that these salt deposits are simply parts of strata of rock salt that have been folded and have perhaps become thicker at the crests of folds.

Potash Salts.—Potash salts are extensively used for fertilizers. Most of the potash salts used in the United States are imported from Germany and from Alsace.

[1] GALE, H. S.: Salt, Borax and Potash in Saline Valley, Inyo County, California. U. S. Geol. Survey *Bull.* 540, pp. 416–422, 1914.

[2] PHALEN, W. C.: Technology of Salt Making in the United States. U. S. Bur. Mines *Bull.* 146, pp. 1–149, 1917.

[3] HARRIS, G. D.: Rock Salt. Its Origin, Geology, and Occurrence. La. Geol. Survey *Bull.* 7, 1908.

[4] FENNEMAN, N. M.: Oil Fields of the Texas-Louisiana Gulf Coastal Plain. U. S. Geol. Survey *Bull.* 282, pp. 119–121, 1906.

HAHN, F. F.: The Form of Salt Deposits. *Econ. Geol.*, vol. 7, pp. 120–135, 1912.

The German potash deposits are sedimentary beds in the Zechstein (Permian). They are near the central part of the republic, and the beds almost surround the Harz Mountains. They occupy extensive areas in Prussian Saxony, Hanover, and the duchies of Anhalt and Brunswick (Fig. 191). Gale[1] states

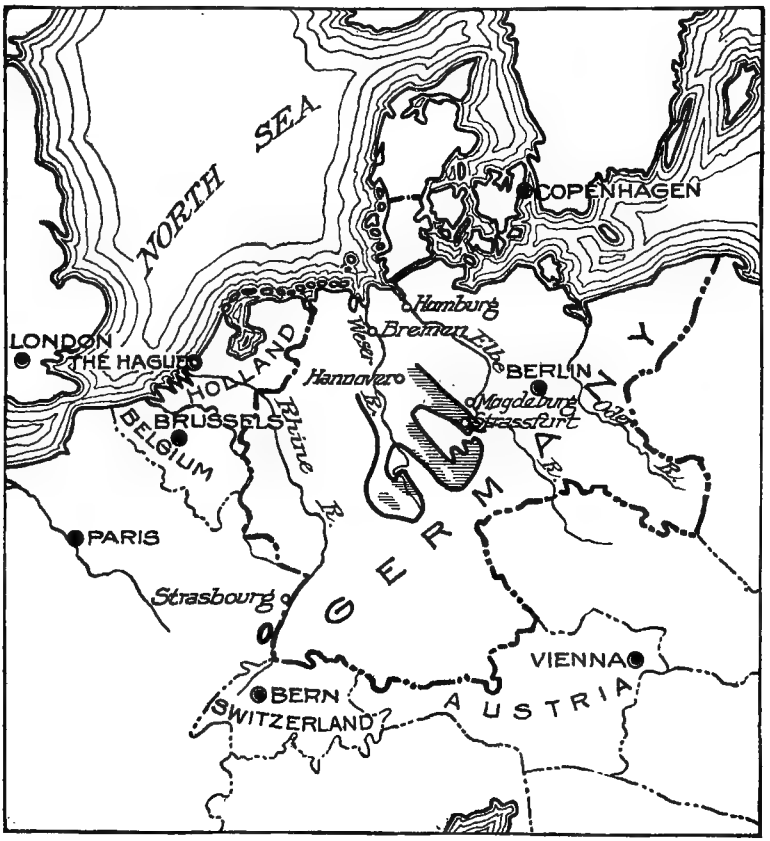


FIG. 191.—Sketch showing location of potash deposits of Germany. (*After Gale.*)

that the reserve is 20,000,000,000 metric tons of crude potash salts. The deposits are sedimentary beds precipitated from salt solutions. The section containing the potash is mentioned on page 341.

[1] GALE, H. S.: Potash. In SPURR, J. E., and others: "Political and Commercial Geology," p. 413, New York, 1920.

The potash deposits of Alsace are in the downfaulted block that lies between the Vosges and the Black Forest (Fig. 192). The beds containing potash are of lower Oligocene age.[1] A section is shown in Fig. 193.

The potash rock, which lies about 1,600 feet below the surface, has an average K_2O content of about 22 per cent. The beds

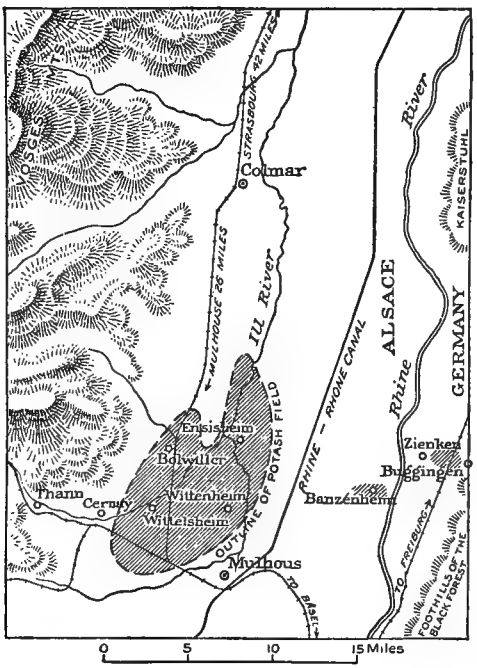


FIG. 192.—Sketch showing position of potash field and valley of the Rhine in the vicinity of Mulhouse, Alsace. (*After Gale.*)

cover a considerable area and are estimated to contain salts that will yield 300,000,000 tons of K_2O. The salts mined are principally chlorides. A peculiar feature of the deposits is the low sulphate content of the potash-bearing rock. An analysis of the material is stated below.

[1] GALE, H. S.: The Potash Deposits of Alsace. U. S. Geol. Survey *Bull.* 715–B, 1920.

COMPOSITION OF POTASH SALTS FROM MAX MINE
[Dr. Horst, analyst.]

KCl	26.75
NaCl	57.43
$CaSO_4$	1.92
$MgCl_2$	0.36
$CaCl_2$	1.26
H_2O	0.71
Insoluble	11.23
	99.66

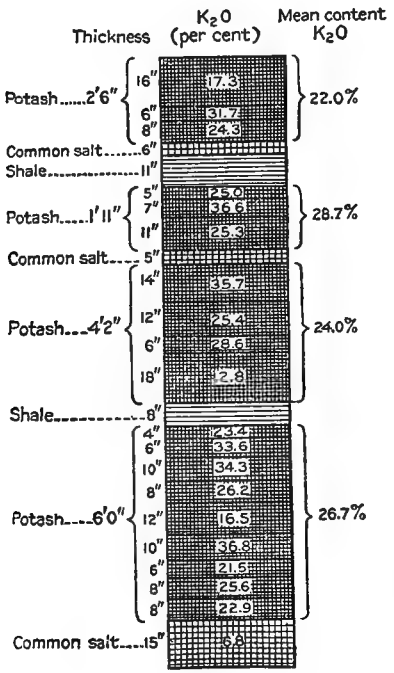


FIG. 193.—Diagram showing lower potash bed in Amélie shaft 1, Wittelsheim, Alsace. (*After M. Louis Bucherer.*)

The deposits are associated with anhydrite and common salt. They have been regarded by many as the sediments precipitated from sea water in a bay or arm cut off from the sea by a barrier. Gale, however, believes that the salts may have been deposited in a closed basin that had no connection with the sea.

In 1920 the United States produced 41,444 tons of potash, valued at $7,463,026. Since then the price and production have greatly declined.

In recent years the United States Geological Survey has been engaged in a search for potash[1] in some form readily available for agriculture. Many lakes, marshes, and playa deposits of California and Nevada have been drilled and sampled. At Searles Marsh, in San Bernardino County, California, a thick salt bed having an area of 11 square miles is saturated with brine with a comparatively high content of potash. A small amount of potash has been recovered from this deposit.

Some igneous rocks carry a percentage of K_2O approximately equal to that of commercial potash salts used for fertilizer. The invention of some smelting process by which the potash of silicates might cheaply be rendered soluble would prove a great service to mankind.

Potash constitutes a considerable percentage of alunite,[2] a mineral that is abundant at Goldfield, Nev., at Marysvale, Utah, and at several other places in the West. By calcination alunite is dehydrated and loses some SO_3, and its potassium sulphate is rendered soluble. Small amounts of potash are obtained by leaching wood ashes, and it has been recovered also from sea weeds, some of which contain potash in notable quantities.

In Nebraska[3] potash has accumulated in muds where waters leaching burned-over prairies have accumulated and dried up.[4] Considerable potash has been obtained from dust recovered in burning Portland cement.

Wyomingite, a lava occurring extensively in the Leucite Hills in Sweetwater County, Wyo.,[5] is composed largely of the mineral

[1] GALE, H. S.: The Search for Potash in the Desert Basin Region. U. S. Geol. Survey *Bull.* 530, pp. 295–312, 1913.

YOUNG, G. J.: Potash Salts and Other Salines in the Great Basin Region. U. S. Dept. Agr. *Bull.* 61, pp. 1–96, 1914.

[2] BUTLER, B. S., and GALE, H. S.: Alunite. U. S. Geol. Survey *Bull.* 511, 1912.

[3] ZIEGLER, VICTOR: The Potash Deposits of the Sand Hills Region of Northwestern Nebraska. Colo. School of Mines *Quart.*, vol. 10, pp. 6–26, 1915.

[4] HANCE, J. H.: Potash in Western Saline Deposits. U. S. Geol. Survey *Bull.* 540, pp. 457–469, 1914.

CONDRA, G. E.: Preliminary Report on the Potash Industry of Nebraska. Neb. Conservation and Soil Survey *Bull.* 8, p. 39, 1918.

COOLBAUGH, W. F.: Potash. Colo. School of Mines *Mag.*, vol. 8, pp. 97–99, 1918.

[5] WELLS, R. C: Experiments in the Extraction of Potash from Wyomingite. U. S. Geol. Survey *Prof. Paper* 98, pp. 37–40, 1917.

leucite, a silicate of alumina and potash. It contains about 11 per cent. K_2O.

According to Cross[1] wyomingite consists of uncombined silica, 22.5 per cent.; leucite, 35.7 per cent.; phlogopite, 22.3 per cent.; diopside, 10.7 per cent.; and accessory minerals, 8.8 per cent. The potash content of wyomingite is distributed among leucite, phlogopite, and a glassy base which is chiefly uncombined silica.

Wells tried the effect of several solvents on wyomingite, and on a mixture of wyomingite and other materials. The best results were obtained by heating mixtures with calcium chloride.

Greensand is unconsolidated material containing glauconite, a hydrous silicate of iron and potassium. Many deposits of greensand contain, in addition to the glauconite and quartz, more or less calcite, commonly in the form of shells or fragments of shells or as cement derived from shells, and a little clay or other fine material, and some deposits contain a little iron phosphate. Greensand deposits containing 3 to 7 per cent. of potash are very abundant in Upper Cretaceous and Eocene rocks in a belt extending from New Jersey to Virginia.[2] The greensand is used for fertilizer, especially in the native state, and it is said that the potash becomes available or soluble when the greensand is in contact with ground water. Although the amount of potash in the greensand is small, the greensand deposits are very large, and if a cheap method of extracting the potash were discovered these deposits would become valuable.

Bromine.—Bromine is found as bromides in sea water and in some deep brines. In Michigan, West Virginia, and Pennsylvania it is obtained from brine incidentally to the manufacture of salt. The lower Carboniferous salt beds are locally high in bromine.[3] An analysis given by Cook[4] states that the brine of a well at Harbor Brook, Mich., owned by the Rand Beach Mineral Springs Co., contains over 11 per cent. of its total solids as

[1] Cross, Whitman: Igneous Rocks of the Leucite Hills and Pilot Butte, Wyo. *Am. Jour. Sci.*, 4th ser., vol. 4, pp. 115–144, 1897.

[2] Ashley, G. H.: Notes on the Greensand Deposits of the Eastern United States. U. S. Geol. Survey *Bull.* 660, pp. 27–49, 1917.

[3] Lane, A. C.: "Mineral Industry," vol. 16, p. 123, 1907. See also volumes of U. S. Geol. Survey "Mineral Resources," especially an article by F. J. H. Merrill in volume for 1904, pp. 1029–1030, 1905.

[4] Cook, C. W.: Preliminary Report on the Salt Industry of Michigan. Mich. Acad. Sci. *Thirteenth Rept.*, pp. 81–86, 1911.

magnesium bromide. Bromine is used in chemistry, as a medium in photography, and as a disinfectant. The United States in 1920 produced 1,160,584 pounds, valued at $745,381.

Calcium Chloride.—Calcium chloride is obtained by the evaporation of salt liquors in Michigan,[1] Ohio, and Pennsylvania. Some is obtained also in connection with the manufacture of soda and other chemical compounds.

The United States in 1920 produced 58,604 short tons of calcium-magnesium chloride, valued at $2,045,851.

Epsomite.—Epsomite ($MgSO_4 \cdot 7H_2O$), which is extensively used for medicine, is manufactured from other magnesium compounds, and some is recovered in the natural state.

On Kruger Mountain, near Oroville, Wash., epsomite is mined from two lake basins, one in the United States, the other in British Columbia.[2] The lakes have no outlets, and the material accumulates by evaporation of waters saturated with magnesium sulphate.

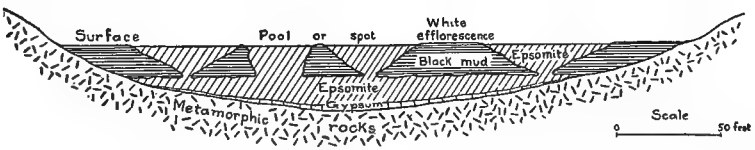


FIG. 194.—Hypothetical vertical cross-section to show structure of small epsomite lake north of Oroville, Wash. (*After Olaf P. Jenkins.*)

The smaller of these lakes is in Washington. It has an area of only 4 acres and a depth of 30 feet. It is high up in the hills, 2,000 feet above sea level, in a depression scooped out by former glacial action. It lies close to bedrock, which consists of metamorphic rocks, dolomites, and shales. Near by, but at a slightly higher elevation, are other smaller lakes or ponds of comparatively fresh water.

The drainage area of this basin is less than half of a square mile. In this area are numerous metalliferous deposits which consist largely of pyrite and pyrrhotite bodies. The oxidation of iron sulphide deposits has yielded sulphuric acid, which has attacked the magnesium and lime of the dolomites and other

[1] COOK, C. W.: The Brine and Salt Deposits of Michigan. Mich. Geol. Survey *Pub.* 12, pp. 1–118, 1912.

[2] JENKINS, OLAF P.: Spotted Lakes of Epsomite in Washington and British Columbia. *Am. Jour. Sci.*, 4th ser., vol. 46, pp. 638–644, 1918.

rocks. The lime and magnesium sulphates were precipitated by evaporation in the lakes, the gypsum being deposited first (Fig. 194).

Sodium Carbonate.—Sodium carbonate is formed at many places in the arid West where waters of closed basins have evaporated. It is one of the common salts present in "alkali" soils. More than a small quantity impairs the fertility of soil.

At Ragtown, Nevada, sodium carbonate was once produced from a soda lake on a commercial scale.[1] Most of the sodium carbonate of commerce is manufactured from salt and limestone.

Sodium Sulphate.—Sodium sulphate, mirabilite, or Glauber salt ($Na_2SO_4 \cdot 10H_2O$), is deposited in abundance in some inland basins where mineral waters are evaporated. Much of this material is obtained as a by-product in manufacturing hydrochloric acid and other salts and is called "salt cake." The natural product sells at a low price. Sodium sulphate is precipitated from water relatively low in calcium and magnesium before sodium chloride is formed. Its solubility is appreciably affected by slight changes in temperature. At Great Salt Lake, Utah, it is precipitated during the winter and cast up on the shore. In summer it is redissolved. Formerly the harvesters in winter removed the salt from the reach of the waves and collected it at leisure.[2]

Near Laramie and at several other places in Wyoming sodium sulphate has been gathered from small lakes that dry up in the summer. Deposits are known at many places in the arid West.[3] Sodium sulphate is used in the manufacture of paper and glass and for medicine. In some metal mills it is used with oils to assist in the flotation of sulphide minerals in their separation from their gangue.

Gypsum.—Gypsum ($CaSO_4 \cdot 2H_2O$) occurs in beds and is commonly associated with salt. Sea water contains a considerable proportion of calcium sulphate, which on evaporation is deposited before sodium chloride. Although gypsum is commonly formed by the superficial alteration of sulphide ores, the principal gypsum deposits are of sedimentary origin. Many of

[1] Chatard, T. M.: Natural Soda, Its Occurrence and Utilization. U. S. Geol. Survey *Bull.* 60, pp. 27–101, 1890.

[2] Talmage, J. E.: "Science," new ser., vol. 14, p. 446, 1880.

[3] Schultz, A. R.: Deposits of Sodium Salts in Wyoming. U. S. Geol. Survey *Bull.* 430, pp. 570–589, 1910.

them are associated with "Red Beds" and have been formed by the evaporation of sea water under arid conditions in inclosed basins or in arms of the sea. Gypsum beds commonly are 20 to 50 feet thick and extend over many square miles.

Anhydrite ($CaSO_4$) is likewise precipitated from sea water. It is not so desirable as gypsum for most purposes. By long exposure anhydrite becomes hydrated, forming gypsum, and some of the workable gypsum beds have been formed in that way.

Extensive gypsum beds occur in many States of the Union. They are widely distributed in Paleozoic and Mesozoic rocks and are found also in the Tertiary. In New York gypsum is interbedded with shales and shaly limestones in the Salina formation (Silurian). The beds worked are from 4 to 30 feet thick. Some of the deposits are worked underground, and others are quarried. The gypsum-bearing area, which is 150 miles long, lies a few miles south of and parallel to the south shore of Lake Ontario.[1]

In northern Ohio gypsum is found in the Monroe formation (Silurian). In Michigan[2] gypsum is mined from deposits interstratified with lower Carboniferous shale and limestone.

In Iowa, near Fort Dodge,[3] gypsum, probably of Permian age, is mined. Locally it rests on the "Coal Measures" and is covered with glacial drift. The gypsum bed is from 10 to 25 feet thick.

In southwestern Virginia[4] gypsum associated with salt and anhydrite is found in Carboniferous gray and red clays. The rocks dip 25° to 45°, and some beds are 30 feet thick.

In Kansas[5] gypsum deposits are mined in a belt that extends northeastward across the State. The beds are associated with Permian red shales. Some of the Kansas deposits have been formed by solutions that dissolved rock gypsum from the beds and precipitated the calcium sulphate in swamps and marshes

[1] NEWLAND, D. H., and LEIGHTON, HENRY: Gypsum Deposits of New York. N. Y. State Mus. *Bull.* 143, 1910.

[2] GRIMSLEY, G. P.: The Gypsum of Michigan and the Plaster Industry. Mich. Geol. Survey, vol. 9, part 2, 1904.

[3] WILDER, F. A.: Geology of Webster County. Iowa Geol. Survey *Ann. Rept.*, vol. 12, pp. 65–235, 1901.

[4] ECKEL, E. C.: Salt and Gypsum Deposits of Southwestern Virginia. U. S. Geol. Survey *Bull.* 213, pp. 406–416, 1903.

[5] GRIMSLEY, G. P., and BAILEY, E. H. S.: Special Report on Gypsum and Gypsum Cement Plasters. Kans. Univ. Geol. Survey, vol. 5, p. 82, 1899.

near by (Fig. 195) as gypsite, an impure unconsolidated mixture of gypsum and clay, or of gypsum, clay, and sand. The material is used for making wall plaster.

Large gypsum deposits are found in western Oklahoma and around the Black Hills, South Dakota[1] (Fig. 196).

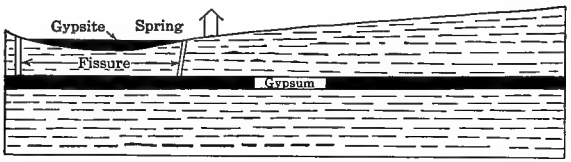


FIG. 195.—Sketch illustrating origin of gypsite or impure gypsum at surface by solution of beds and evaporation of water issuing through fissures.

In New Mexico[2] a gypsum bed 60 feet thick is associated with limestone, red shale, and pink sandstone in the "Red Beds." Gypsum is mined in Lyon County, Nevada.[3] In southern California, in eastern Riverside County,[4] a gypsum bed is found in metamorphosed rock, probably of pre-Cambrian age.

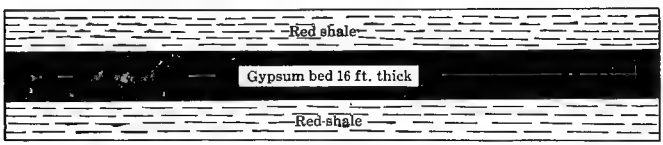


FIG. 196.—Section of Spearfish formation (Truassic?) north of Black Hills, South Dakota.

Regional metamorphism has converted it to selenite. Later it was intruded by diorite and metamorphosed near the contact to anhydrite and to a friable white powder.

Gypsum is used in the manufacture of wall plaster, land plaster, stucco, plaster of Paris, and various cements. The ground powder, unburned, is used to retard the set of Portland cement. Land plaster is powdered gypsum, unburned, used for fertilizer.

[1] O'HARRA, C. C.: South Dakota School of Mines *Bull.* 8, 1908.

[2] SHALER, M. K.: Gypsum in Northwestern New Mexico. U. S. Geol. Survey *Bull.* 315, pp. 260–266, 1907.

[3] JONES, J. C.: The Origin of Anhydrite at the Ludwig Mine, Lyon County, Nevada. *Econ. Geol.*, vol. 7, pp. 400–403, 1912.

[4] HARDER, E. C.: The Gypsum Deposits of the Palen Mountains, Riverside County, California. U. S. Geol. Survey *Bull.* 430, pp. 407–416, 1910.

The white powder is used in making paint, crayons, and paper and for an adulterant. White massive gypsum (alabaster) is used by sculptors for making ornaments. Gypsite is used for making wall plaster, in which the clay serves as a retarder. Plaster boards, building blocks, and various other forms are made from gypsum plaster.[1]

Gypsum contains, besides combined water, a variable content of absorbed moisture. If it is heated to a temperature between 212° and 400° F., depending on the impurities it contains, the free moisture and part of the combined water are driven off: $CaSO_4 \cdot 2H_2O$ becomes $2CaSO_4 \cdot H_2O$. The partly dehydrated material is ground, and when water is added it sets again, forming more highly hydrated calcium sulphate. If it is raised to too high a temperature the gypsum becomes "dead burned" and will not readily set on addition of water. The production of gypsum in the United States in 1920 amounted to 3,129,142 tons, valued at $24,533,065.

Boron Compounds.—Boron is a comparatively rare element. It is present in the silicates, tourmaline, axinite, and datolite, but these are not important as sources of boron. Borax compounds are present also in many hot springs. In arid regions borax salts are formed by the evaporation of water in closed basins. Nearly all the boron compounds of commerce are obtained from bedding-plane deposits of borax minerals that are interlayered with sedimentary rocks. These are found principally in areas of late volcanic activity.

The water of Clear Lake, California,[2] contains an unusual proportion of boron compounds. Formerly the water was evaporated for borax salts on a commercial scale. The solid matter in a spring on the margin of this lake contains 25.61 per cent. B_4O_7.

The principal borax minerals are colemanite ($Ca_2B_6O_{11}.5H_2O$), borax ($Na_2B_4O_7.10H_2O$), ulexite ($CaNaB_5O_9.8H_2O$), and boracite ($Mg_7Cl_2B_{16}O_{30}$). Of these, colemanite supplies practically the total output of borax in the United States. A little boracite is obtained from the Stassfurt region, Germany, and some borates

[1] Burchard, E. F.: Gypsum. U. S. Geol. Survey *Mineral Resources*, 1910, part 2, pp. 717–733, 1911 (contains bibliography and a map showing distribution of gypsum plants in the United States).

[2] Becker, G. F.: Geology of the Quicksilver Deposits of the Pacific Slope. U. S. Geol. Survey *Mon.* 13, pp. 265, 440, 1888.

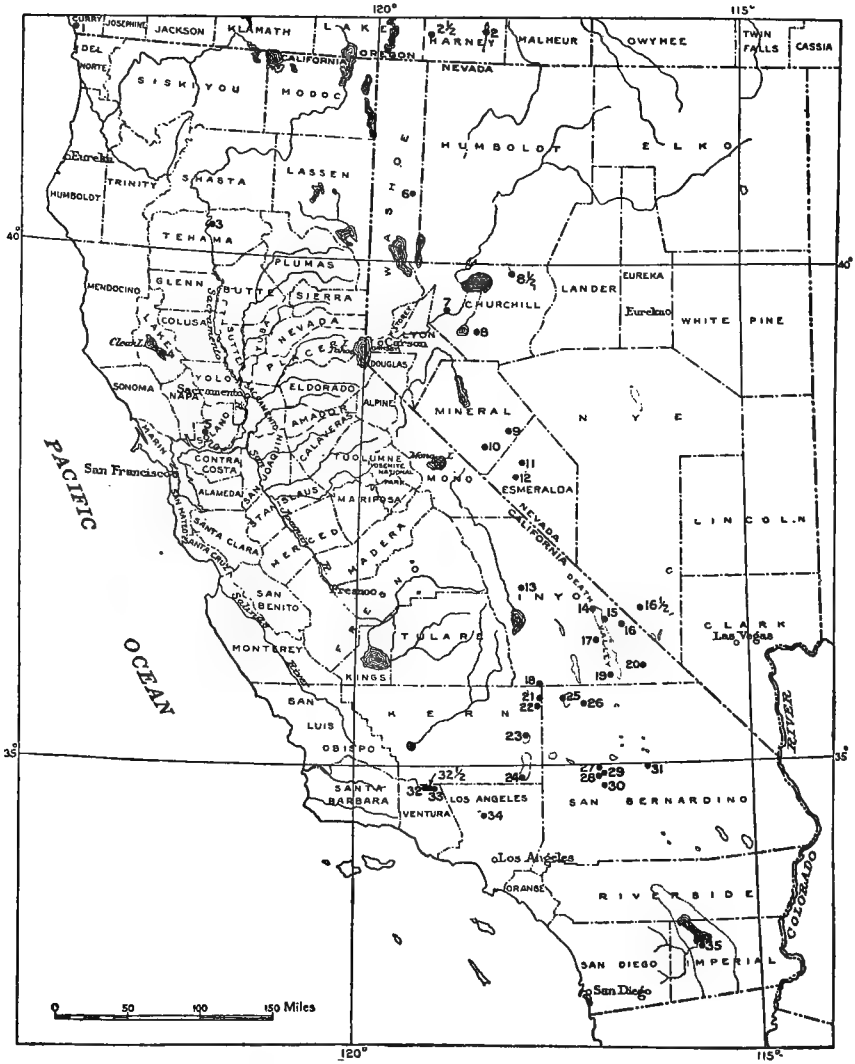


FIG. 197.—Map showing borax deposits in the United States. (*After Gale.*)

1. Chetco, Curry County, Ore. Priceite was mined.
2. Marsh deposits near Lake Alvord, Harney County, Ore.

2½. Marsh deposits near Warner Lake, Harney County, Ore.

3. Tuscan Springs, Tehama County, Cal. First discovery of borated waters by Veatch.
4. Clear Lake, Lake County, Cal. First workings in California.
5. Solano beds, Fairfield, Solano County, Cal.
6. Hot Springs waters at Gerlach, Washoe County, Nev. Borax plant established at one time.
7. Soda Lakes (Ragtown Ponds), near Fallon, Churchill County, Nev.
8. Salt Wells, Churchill County, Nev. Old marsh borax plant.

8½. Dixie Valley, Churchill County, Nev. Marsh borax.

9. Rhodes Marsh, Esmeralda County, Nev. Former large workings.
10. Teels Marsh, Esmeralda County, Nev. Former large workings.

Legend continued on page 355.

are recovered as by-products from the evaporation of brines. Pandermite is a lime borate near colemanite in composition, but it does not decrepitate on heating and is not used at present.

Boron minerals are found in both syngenetic and epigenetic deposits. Some have been formed probably by the evaporation of waters that have leached older bedded deposits. Some of the older deposits are doubtless the result of desiccation of hot-spring waters in ancient closed basins; others have been formed in fissures and fractured zones. The soluble borax minerals[1] are removed readily from outcrops. Some outcrops of colemanite are marked by gypsum.

The Lila C. borax mine, in Death Valley, California (Fig. 197), is at present the principal source of borax.[2] The borax beds are associated with Tertiary shales, sandstones, and vesicular lavas. The strata are deeply tilted and faulted. The borax beds, which occur at definite stratigraphic horizons, dip about 45.° The principal borax mineral is colemanite, the beds of which are locally 15 feet or more thick.

[1] GALE, H. S.: The Origin of Colemanite Deposits. U. S. Geol. Survey *Prof. Paper* 85, pp. 1–9, 1913.

[2] GALE, H. S.: The Lila C. Borax Mine at Ryan, Calif. U. S. Geol. Survey *Mineral Resources*, 1911, part 2, pp. 861–866, 1912.

CAMPBELL, M. R.: Reconnaissance of the Borax Deposits of Death Valley and Mohave Desert. U. S. Geol. Survey *Bull.* 200, pp. 1–23, 1902.

11. Columbus Marsh, Esmeralda County, Nev. Former large workings.
12. Fish Lake Valley, Esmeralda County, Nev. Marsh deposits; former large workings.
13. Saline Valley, Inyo County, Cal. Marsh deposits; former workings.
14. Coleman (Furnace Creek ranch), Inyo County, Cal. Main works of the 20-mule teams, 1883.
15. Mount Blanco, and other deposits on Furnace Creek, Inyo County, Cal. Large undeveloped deposits of colemanite.
16. Lila C. mine, Ryan, Inyo County, Cal. Colemanite. Property of Pacific Coast Borax Co.; largest producer.

16½. Ash Meadows, Nev., borate spring waters.

17. Panamint Range, Inyo County, Cal. Colemanite reported.
18. El Paso Peak, Inyo County, Cal. Colemanite reported.
19. South end of Death Valley, Inyo County, Cal. Colemanite reported.
20. Resting springs, Zabriskie, Inyo County, Cal. Worked in 1883.
21. China Lake (Mesquite Springs), Kern County, Cal. Worked in 1883.
22. Colemanite reported.
23. Cane Lake, Kern County, Cal. Marsh deposits formerly worked.
24. Rodriguez Lake, Kern County, Cal. Borax locations; never produced.
25. Searles Lake, San Bernardino County, Cal. Marsh deposits formerly worked.
26. Slate Range, San Bernardino County, Cal. Colemanite reported.
27. Town of Borate, San Bernardino County, Cal. Formerly principal works of Pacific Coast Borax Co.
28. American Borate Co.'s works, San Bernardino County, Cal.
29. Palms Borate Co.'s mine and plant, San Bernardino County, Cal.
30. Property of Palms Borate Co., San Bernardino County, Cal.
31. Mohave Canyon borax mine, San Bernardino County, Cal.
32. Frazier mine, Ventura County, Cal. Colemanite.

32½. Russell Borate Mining Co.'s mine, Ventura County, Cal. Colemanite.

33. National Borax Co. (old Columbus mine), Ventura County, Cal. Colemanite.
34. Lang, Los Angeles County, Cal. Sterling Borax Co.; colemanite; large producer.
35. Mud Volcanoes, Imperial County, Cal. Borax present in waters.

At Stauffer, Ventura County, California, colemanite deposits occur in folded and faulted sedimentary rocks closely associated with beds of basalt that inclose zones of shale and massive limestone. The limestone beds contain the largest borate deposits in the field. The limestone is sheeted, shattered, and cemented and partly replaced by colemanite.

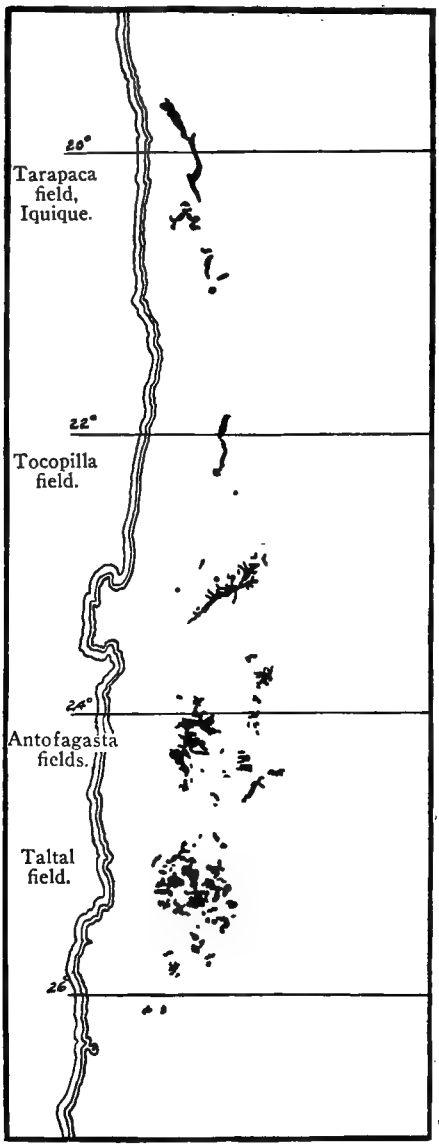


FIG. 198.—Sketch of part of Chile showing location of principal nitrate fields. (*Based on map by Whitehead.*)

Borax compounds are used for preservatives, in chemistry, as cleansers and insecticides, and for making glass, paints, cosmetics, etc. The United States produced in 1920 about 120,320 tons of borates, valued at $2,173,000.

Nitrates.—Sodium nitrate ($NaNO_3$, Chile niter) and potassium nitrate (KNO_3, saltpeter) are readily soluble in water and therefore are found only in arid regions or in caves or other places where they are protected from rain. These salts are formed by the decomposition of organic waste through the agency of nitrifying bacteria. Nitrate deposits occur in Death Valley, California, and at other places in the United States, but these are probably of small value.

Nitrates are used for making fertilizers, dyes, and explosives. Large amounts are used also in the chamber process of making sulphuric acid, although most of that so used is recovered, and used again.

The world's supply of nitrates is obtained mainly from the Atacama and Tarapaca desert regions of Chile. This region has produced nitrates valued at about $2,000,000,000. In recent years[1] it has yielded annually about 3,000,000 metric tons, valued at $150,000,000. The impure nitrate mixtures are refined by dissolving in hot water and by fractional crystallization.

The deposits are found in the arid valley between the Coast Range and the Andes and extend over an area 400 miles long (Fig. 198). The mountain ranges contain many flows and intrusions of late geologic age. The nitrate deposits are found in the gravelly detritus of the mountains and generally lie within 2 to 20 feet of the surface, rarely as deep as 20 feet (Fig. 199). The country is extremely arid, and during the topographic development of the desert the salts that have formed have been deposited with the gravels on the hill slopes or have been carried to the basins.[2]

In general there is below a thin veneer of gravel a zone of sodium sulphate. Below that sodium chloride appears, and still lower sodium nitrate predominates. Thus the salts tend to arrange themselves in the order of their solubilities, the least soluble salt being precipitated near the surface and the most soluble salt at the greatest depth. The thickness[3] of the blanket of salts ranges from a few inches to several feet, and the blanket descends with the surface of the gravels.

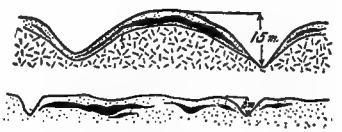


FIG. 199.—Sections showing relations of caliche (black) to surface, and to minor water courses in Peñon deposits. Dotted area is gravel; dashed area is rock. (*After Whitehead.*)

Over the origin of the Chile nitrate deposits there is much controversy. One hypothesis is that the nitrates of the caliche[4] have been derived from

[1] ROGERS, A. H., and VAN WEGEMAN: The Chilean Nitrate Industry. Am. Inst. Min. Eng. *Trans.*, vol. 59, pp. 6–26, 1918.

[2] WHITEHEAD, W. L.: The Chilean Nitrate Deposits. *Econ. Geol.*, vol. 15, pp. 187–224, 1920.

[3] STRAUSS, L. W.: The Chilean Nitrate Industry. *Min. and Sci. Press*, vol. 108, p. 972, 1914.

[4] The earthy nitrate salt in natural state.

the air by oxidation of nitrogen through the agency of static electricity.[1] Nitrates are produced artificially by oxidation of nitrogen of the air in the electric arc. It is said, however, that electrical effects are not more pronounced in the desert regions of Chile than in other desert regions where nitrates do not accumulate. Another theory is that the nitrate mixture has been derived from the leaching of material formed by the action of nitrifying bacteria on organic matter in the soil.[2] This organic matter is supposed to be in part of animal origin. Guano deposits occur in parts of the nitrate region. Penrose[3] considers it probable that the deposits have originated through the leaching of nitrate from extensive deposits of bird guano that accumulated before the coast range was thrown up, the leachings having mingled with the salines of a closed basin.

Although the country is extremely arid, ground-water nevertheless stands in places near the surface, being supplied by the mountains near the border. Singewald and Miller[4] note that the nitrate deposits occur at the places where the ground water comes near the surface and where the soil is porous and believe that the accumulation of nitrates is due to abnormally rapid evaporation of great quantities of ground water under extremely arid conditions. They also believe, however, that the quantities of nitrates carried by the water are above the average, and they note the presence of skeletons of birds and guano in the desert basin.

The original sources of the nitrates, according to Singewald and Miller, and also to Whitehead, are the volcanic rocks of the region. Whitehead says that all the deposits are found near bodies of tuffs or lavas. Where intrusive rocks predominate and the rocks are silicified and where tuffs are absent there are no nitrate beds of consequence. Both Whitehead and Clarke[5] suggest that the nitrates are derived from volcanic sources.

[1] Semper, E., and Michels: Die Saltpeterindustrie Chiles. *Zeitschr. Berg-, Hütten- u. Salinenwesen preuss. St.*, vol. 52, pp. 359–482, 1904.

[2] Müntz, A.: Recherches sur la formation des gisements du nitrate de soude. *Compt. Rend.*, vol. 101, pp. 1265–1267, 1885.

[3] Penrose, R. A. F., Jr.: The Nitrate Deposits of Chile. *Jour. Geol.*, vol. 18, pp. 1–32, 1910.

[4] Singewald, J. T., Jr., and Miller, B. L.: The Genesis of the Chilean Nitrate Deposits. *Econ. Geol.*, vol. 11, pp. 103–114, 1916.

[5] Clarke, F. W.: The Data of Geochemistry. U. S. Geol. Survey *Bull.* 616, p. 258, 1916.

The deposits contain boron, and boron and ammonia are present in some hot springs. Waters containing ammonia salts, collecting in lagoons in the presence of bacteria, would yield nitrates, which would be found in the dried residue.

Singewald and Miller attribute the concentration of the salts principally to capillary migration and evaporation near the surface. Whitehead believes that the salts have been dissolved by a meager supply of water that moved downward and was subsequently evaporated.

ANALYSES OF CALICHE
(After Whitehead)

	A	*B*	*C*	*D*
$NaNO_3$	28.54	53.50	22.73	27.08
KNO_3	Trace	17.25	1.65	1.34
NaCl	17.20	21.28	41.90	8.95
$CaCl_2$	.....	.....	.....	5.25
$MgCl_2$	.....	.....	.....	0.18
$KClO_4$	Trace	0.73	Trace	Trace
Na_2SO_4	5.4	1.93	0.94	None
$MgSO_4$	3.43	1.35	3.13	None
$CaSO_4$	2.67	0.48	4.80	2.89
$Na_2B_4O_7$	0.49	0.56	0.53	0.52
NaI	0.047			
$NaIO_3$	0.033	0.01	0.07	0.08
NH_4 salts	Trace	Trace	Trace	Trace
Na_2CrO_4	.....	Trace	Trace	
Insoluble	40.39	2.07	22.50	47.34
H_2O	1.88	0.70	1.75	6.37
	100.00	100.00	100.00	100.00

Caliche mined is usually 14–25 per cent. $NaNO_3$. *B* is material now seldom found in quantity.

Iodine.—Iodine is a rare element in the earth's economy. It is found in small amounts in many silver mines combined with silver ores as the iodide or as silver iodobromide. All the iodine of commerce is obtained by treating the ash of kelp or from the liquors utilized in the refining of soda niter in Chile. From the latter source about 700 tons of iodine a year is produced.

CHAPTER XV

PYRITE, SULPHUR, BARIUM AND STRONTIUM MINERALS, FLUORITE AND CRYOLITE

Pyrite and Sulphuric Acid.—Sulphuric acid is the most essential acid used in the industries, corresponding to lime, the chief alkali, and coke, the chief reducing agent. In the chemical industries it is probably used for a greater variety of purposes than any other substance. Its consumption has been looked upon as a criterion of the activity of a country in chemical manufactures in general. In a state more or less dilute sulphuric acid is used for many purposes[1] for example, in the manufacture of sulphate of soda, soda ash, bleaching powder, soap, glass, phosphates and many acids; in preparing phosphorus, iodine, bromine, and the sulphates; in the metallurgy of copper, cobalt, nickel, platinum, silver; for cleaning sheet iron to be tinned or galvanized; for working galvanic cells in electroplating, etc. for purifying many mineral oils, and for manufacturing parchment paper; starch, sirup, and sugar; for the saccharification of corn; in dyeing, calico printing and tanning.

It is used in a concentrated state for manufacturing the fatty acids; purifying benzene, petroleum, paraffin oil, and other mineral oils; drying air, refining gold and silver, desilvering copper, etc.; making indigo; preparing many nitro compounds and nitric ethers, especially in manufacturing nitroglycerin, pyroxylin, nitrobenzene, picric acid, etc.

Pyrite, marcasite, pyrrhotite, sphalerite, and sulphur are used for making sulphuric acid. The roasted minerals give off sulphur dioxide, which is led into a Glover tower, where nitrogen oxides and steam are introduced. Sulphur dioxide is oxidized to sulphur trioxide, with which a molecule of water unites, forming sulphuric acid. Part of the nitrogen compounds after having oxidized the sulphur dioxide are recovered in Gay-Lussac towers. Thus the process with respect to nitrogen is regenerative.

[1] LUNGE, G.: Manufacture of Sulphuric Acid and Alkali, vol. 1, part 2, pp. 1169–1170, 1903.

The great acid plants in the Ducktown district, Tennessee, use blast-furnace gases obtained from smelting pyrrhotite-chalcopyrite copper ores. Some plants make acid from fumes obtained by roasting sphalerite as a preliminary to charging it in zinc retorts. Marcasite is obtained by separating the iron sulphide from zinc sulphide in zinc concentrates. The principal output of marcasite comes from the zinc ores of southwestern Wisconsin and northwestern Illinois.

Pyrite is mined in several Eastern States, and considerable pyrite is now obtained as a by-product of coal mining in Illinois, Indiana, and Ohio. At some plants the cinder obtained from burning pyrite for acid making is subsequently leached for the extraction of copper and smelted for iron. Pyrite is imported from Canada and Spain. The Spanish pyrite from the Huelva or Rio Tinto region is of high grade and abundant. It is received in large quantities at eastern ports.

Virginia is an important producer of domestic pyrite. In Louisa County there are huge lenticular deposits of pyrite in garnet-mica schist which is probably a metamorphosed limestone.[1] Minerals associated with the pyrite include chalcopyrite, galena, sphalerite, pyrrhotite, magnetite, actinolite, calcite, and garnet. The lenses of pyrite ore are rudely in alignment or overlap. According to Watson they have replaced sedimentary beds. Pyritic lenses in schist are worked also in Prince William County, Virginia. In St. Lawrence County, New York,[2] near Canton and Gouverneur, deposits of low-grade pyrite in schist are mined and concentrated. At the Davis mine, Franklin County, Massachusetts, a deposit of high-grade pyrite in schist was mined for many years but is said now to be exhausted. At the Milan mine, New Hampshire,[3] a pyritic deposit in schist is mined and concentrated for pyrite. Considerable pyrite is mined in California in the foothill copper belt and in Shasta County

In 1920 the United States produced about 275,000 long tons of pyrite, valued at $1,450,000.

Sulphur.—Although sulphur is present in sulphides in most lode deposits of the metals, native sulphur forms only sparingly by

[1] WATSON, T. L.: "Mineral Resources of Virginia," p. 190, Lynchburg, 1907.

[2] SMYTH, C. H., JR.: On the Genesis of the Pyrite Deposits of St. Lawrence County. N. Y. State Mus. *Bull* 158, p. 143, 1912.

[3] EMMONS, W. H.: Some Ore Deposits of Maine and the Milan Mine, New Hampshire. U. S. Geol. Survey *Bull.* 432, pp. 50–60, 1910.

oxidation of sulphide ores, and lode deposits produce little commercial sulphur. The sulphur supply is obtained from sedimentary beds that carry sulphur, from deposits formed near volcanic vents and at the orifices of hot springs that yield hydrogen sulphide, and from extinct volcanic and fumarolic centers. The sulphur has evidently been formed near the surface by the oxidation of hydrogen sulphide. In the presence of oxygen the following reaction probably takes place:

$$H_2S + O = H_2O + S$$

The largest sulphur deposits are found in Calcasieu Parish,[1] Louisiana. Below about 400 feet of unconsolidated sandstone is a bed of gypsum and sulphur with some organic matter. The deposits were discovered in boring for oil, and attempts were made to sink shafts to them, but that was found to be impracticable in the loose sandy beds overlying the sulphur beds. The deposits are now successfully worked by the Frasch process. Two pipes, one inside the other, are sent down to the sulphur bed, and superheated water or steam is discharged through one pipe at the bottom of the well, melting the sulphur, which rises with the hot water through the other pipe and solidifies on cooling in the air. The process also refines the sulphur, a pure product being obtained.

The deposits occupy a dome in Cretaceous sedimentary rocks. The area has been outlined by drilling and is rudely circular and over half a mile in diameter. The sulphur bed is locally more than 100 feet thick, and much of it contains about 70 per cent. of sulphur. The sulphur is associated with limestone and gypsum and is underlain by gypsum. These deposits contain large reserves.

Valuable deposits of sulphur are found also near Bryan Heights, Texas, in a structural dome that has yielded oil and gas. The sulphur is associated with salt, gypsum, and limestone.[2] Sulphur is found also in a dome; near Matagorda, and in Hoskins Mound, Texas.

Before the development of the Frasch process and the exploi-

[1] HAYES C. W., and KENNEDY, WILLIAM: Oil Fields of the Texas-Louisiana Gulf Coastal Plain. U. S. Geol. Survey *Bull.* 212, pp. 133–135, 1903.
HARRIS, G. D.: Oil and Gas in Louisiana. U. S. Geol. Survey *Bull.* 429, pp. 99–103, 1910.

[2] PHALEN, W. C.: Sulphur, Pyrite, and Sulphuric Acid. U. S. Geol. Survey *Mineral Resources*, 1912, part 2, pp. 931–953, 1913.

tation of the Louisiana deposits Sicily was the chief source of the world's supply of sulphur. The Sicilian deposits lie in tilted Miocene strata and are associated with Miocene limestone and gypsum. The situation of these deposits near Mount Etna and the presence of numerous solfataras on the island early led to the assumption that the sulphur had been formed through the agency of hydrogen sulphide and other sulphur gases known to be exhaled by volcanoes. Similar deposits, however, are found associated with limestone and gypsum remote from centers of volcanic activity, and it is now believed that the deposits are not genetically related to volcanism. The sulphur in these deposits is believed by many to be of syngenetic origin,[1] although the method of their formation is not yet clearly elucidated.

The origin of sulphur beds has long been a subject of controversy. It is supposed by some that organic matter has reduced gypsum, forming calcium sulphide, which was further decomposed by carbon dioxide and oxygen, yielding calcium carbonate and sulphur, $2C + CaSO_4 = CaS + CO_2$. This reaction has not been verified experimentally, and the genesis of these deposits is still in doubt. A plausible hypothesis has been stated by Hunt,[2] who believes that the sulphur is formed by the destruction of gypsum through the agency of certain anaerobic bacteria that consume calcium sulphate and liberate hydrogen sulphide. Such organisms are now active in the Black Sea. The oxidation of the hydrogen sulphide would set free sulphur, as noted above.

At Sulphurdale, Utah,[3] and at Cody, Wyo.,[4] sulphur has been deposited in shattered lavas, probably by hydrogen sulphide gases At Cody such gases now issue copiously from vents near sulphur deposits. At Thermopolis, Wyo.,[5] sulphur is

[1] Stutzer, Otto: "Die wichtigsten Lagerstätten der Nicht-Erze," p. 474, Berlin, 1911. Translated by Phalen, W. C.: *Econ. Geol.*, vol. 7, pp. 732–745, 1912.

[2] Hunt, W. F.: The Origin of Sulphur Deposits in Sicily. *Econ. Geol.*, vol. 10, pp. 543–579, 1915.

[3] Lee, W. T.: The Cove Creek Sulphur Beds, Utah. U. S. Geol. Survey *Bull.* 315, pp. 485–489, 1907.

[4] Woodruff, E. G.: Sulphur Deposits at Cody, Wyo. U. S. Geol. Survey *Bull.* 340, pp. 451–456.

[5] Woodruff, E. G.: Sulphur Deposits near Thermopolis, Wyoming. U. S. Geol. Survey *Bull.* 380, pp. 373–380.

Hewett, D. F.: Sulphur Deposits of Sunlight Basin, Wyoming. U. S. Geol. Survey *Bull.* 530, pp. 350–362, 1913.

obtained below travertine that rests on limestone. Sulphur is found also in western Texas.[1]

Sulphur deposits are situated in the belt of active and quiescent volcanoes that extends throughout the Alaska Peninsula,[2] the Aleutian islands, and Japan, especially at Makushin volcano, in the northern part of Unalaska Island, about 12 miles west of Dutch Harbor. This is a volcanic pile built up of alternating accumulations of basaltic lava, scoria, lapilli, and dust. In shape it is a broad dome, which forms a prominent feature of the landscape on account of its snow and ice capped summit and flanks. The sulphur deposit is a short distance southwest of the center of the crater. It is composed chiefly of siliceous residual products of rock decomposition that have resulted from the corrosive chemical action of the hot solfataric vapors on basalt. The most conspicuous accumulations of sulphur occur along crevices or large clefts that intersect the surface of the ground in many directions and around the holes from which large volumes of hot vapor issue continuously. The deposit may be divided roughly into two zones: a richer zone that forms a surface layer from 1 to 2 feet thick that seems to owe its crusty character chiefly to the sulphur in it, and a poorer subsoil zone that consists in greater part of moist, hot, porous, decomposed material in which a small percentage of sulphur is disseminated locally to a depth of 15 to 20 feet at some places.

In Hokkaido, Japan, sulphur is recovered from an old volcanic crater. Sulphur is said to occur in commercial quantities near Popocatepetl, Mexico, and other volcanoes.

A large part of the sulphur produced is utilized in the paper industry, in which it is converted into sulphite and used for bleaching paper pulp. Much sulphur is now used in making sulphuric acid. Because sulphur ignites at a low temperature it is used in making matches, gunpowder, and fireworks. Sulphur dioxide is used extensively for bleaching. Sulphur is used for spraying vegetation to protect it against fungous diseases, as a preservative, and for vulcanizing rubber.

In 1920 the United States produced 1,517,625 long tons of

[1] THOMAS, KIRBY: Sulphur Deposits in the Trans-Pecos Region in Texas. *Eng. and Min. Jour.*, vol. 106, p. 979, 1918.

[2] MADDREN, A. G.: Sulphur on Unalaska and Akun Islands and near Stepovak Bay, Alaska. U. S. Geol. Survey *Bull.* 692, pp. 283–298, 1919.

sulphur, valued at $30,000,000. Most of this was from Louisiana, Texas, Nevada, and Wyoming.

Barite.—Barite ($BaSO_4$) is a common gangue mineral in ore veins, especially in those formed at intermediate and shallow depths. In deposits of the deep zone, in contact-metamorphic deposits, and in pegmatites barite is rarely present. Igneous rocks commonly contain the barium silicate molecule in feldspars. The sulphate is present in appreciable amounts in many sedimentary rocks. Barite veins are common in the West, where igneous activity has been prominent, but barite is probably deposited also from normal ground water. Buckley suggests that the deposits of Washington County, Missouri, have been precipitated as sulphate from ground water in which barium was carried as bicarbonate. W. A. Tarr, however, has suggested a magmatic source of the barite-depositing waters. Barite is difficultly soluble, and in weathering it collects with clay and iron oxide in the mantle rock. Nearly all the barite produced in the United States is associated with weathered limestones. It could doubtless be recovered profitably from many lode deposits of the West if markets or transportation facilities were more favorable. The production of barite in the United States in 1920 was 207,700 short tons, valued at $1,946,800. The price, less than $10 a ton, is for the natural or hand-picked material at points of production. Ground and refined barite is worth more.

Barite[1] is used for making paints, especially in the manufacture of lithopone, a white paint consisting of barium sulphate and zinc sulphide made by a complex process involving the reduction of barite at high temperature. Lithopone is used in great quantities for interior finish, the white finish having become popular largely as a result of indirect lighting, which has been made possible by the tungsten filament in electric bulbs. Lithopone is used also for making linoleum, oil cloth, and shades. Ground barite is used for mixing with other pigments, and it is said to give "tooth" to a coat of paint so that the second or third coat will adhere. It is used also for treating rubber, for filling paper, and for tanning. In preparing barite it is ground, and if it is stained by iron oxide the oxide is dissolved by treatment with dilute sulphuric acid and steam.

[1] GARDNER, H. A., and HECKELL, G. B.: Barite as a Pigment. Am. Inst. Min. Eng. *Trans.*, vol. 50, p. 983, 1914.

HILL, J. M.: Barites and Strontium minerals. U. S. Geol. Survey *Mineral Resources*, 1915, part 2, pp. 161–187.

The most productive barite deposits in the United States are in Washington County, Missouri, in the region of the disseminated lead deposits (page 469). There Ordovician limestone is capped by residual clay. In the lower part of the clay are numerous fragments of barite, limestone and chert. Small veins and disseminated deposits of barite are found in the limestone.[1]

In some of the veins galena and quartz are present. All the barite is mined near the surface, most of the mines being 40 feet deep or less, although one mine is 105 feet deep. The barite is found in the mantle of residual material above the limestone.

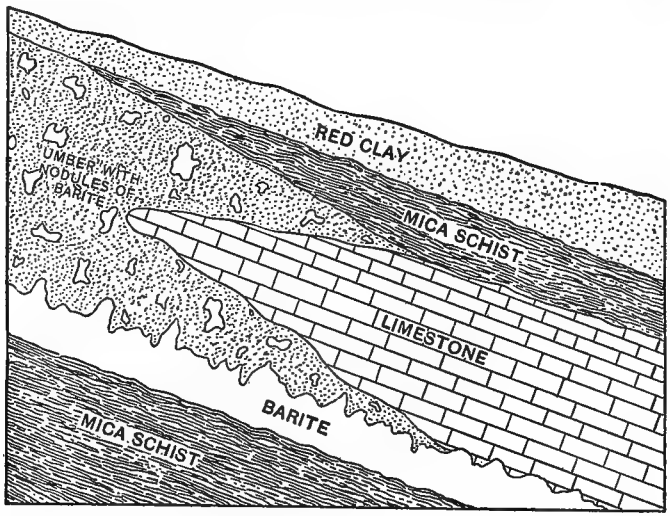


FIG. 200.—Ideal section in Bennett barytes mine, Pittsylvania County, Virginia. (*After Watson.*)

It is associated with chert, quartz, clay, and dolomite, in a sheet-like body. In its upper part and near the surface clay predominates. The barite lies mainly deeper and is recovered through shallow shafts sunk to the barite zone. According to Buckley and to Tarr, the barite has been concentrated by the solution and removal of the limestone.

[1] BUCKLEY, E. R.: Geology of the Disseminated Lead Deposits of St. Francois and Washington Counties, Missouri. Mo. Bureau of Geol. and Mines, vol. 9, part 1, pp. 238–248, 1909.

STEEL, A. A.: Geology, Mining, and Preparation of Barite. Am. Inst. Min. Eng. *Trans.*, vol. 40, pp. 711–743, 1910.

TARR, W. A.: The Barite Deposits of Missouri and the Geology of the Barite District. Mo. Univ. *Studies*, vol. 3 pp. 1–111, 1918.

In Virginia barite deposits are found as irregular pockets replacing pre-Cambrian limestone and as fissure fillings in schists, Paleozoic limestones, and Triassic limestones and shales. The deposits are concentrated by weathering (Fig. 200) and are found in residual clay with iron oxide.[1] Small barite veins are found also in Tennessee.[2]

Large veins of white barite cut limestone and schists in the Ketchikan district and near Wrangell, Alaska.[3]

In Canada veins of barite are found at Lake Ainslee, Cape Breton,[4] cutting felsite, and near Five Islands, Nova Scotia,[5] filling fissures in Devonian sedimentary rocks. The latter, according to Warren, have probably been formed by hot waters.

Barite is found at many places in Europe and formerly was imported in considerable quantities from Germany, where it is mined in Permian and Triassic rocks. It is mined also in England, Belgium, France, and Italy.

Witherite.—Witherite ($BaCO_3$) occurs in veins and is found as a gangue mineral of a few metalliferous veins. It is abundant at Fallowfield, near Hexham, Northumberland, England, where it occurs with barite in fissures that cut Carboniferous rocks. It is found in the Rabbit Mountains, near Thunder Bay, Lake Superior. Barium salts are used for making glass, for making fireworks, and in the refining of beet sugar. Witherite is not mined in the United States.

Strontium Minerals.—Small amounts of strontium are found in igneous rocks. It is probably present in small amounts in the alkali and alkaline earth feldspars. The earth's crust, according to Clarke,[6] contains 0.04 per cent. of SrO.

[1] WATSON, T. L.: Geology of Virginia Barite Deposits. Am. Inst. Min. Eng. *Trans.*, vol. 38, pp. 710–733, 1907.

[2] GORDON, C. H.: Barite Deposits of the Sweetwater District, East Tennessee. "Resources of Tennessee;" vol. 8, 1, pp. 48–82, Tenn. Geol. Survey, 1918.

WATSON, T. L., and GRASTY, J. S.: Barite of the Appalachian States. Am. Inst. Min. Eng. *Trans.*, vol. 51, pp. 514–559, 1915.

[3] BURCHARD, E. F.: A Barite Deposit near Wrangell. U. S. Geol. Survey *Bull.* 592, pp. 109–117, 1914.

[4] POOLE, H. S.: The Barite Deposits of Lake Ainslee and North Chilicamp, Nova Scotia. Canada Geol. Survey *Pub.* 953, pp. 12–40, 1907.

[5] WARREN, C. H.: Barite Deposit Near Five Islands, Nova Scotia. *Econ. Geol.*, vol. 6, pp. 799–807, 1911.

[6] CLARKE, F. W.: The data of Geochemistry, 3d ed. U. S. Geol. Survey *Bull.* 616, p. 32, 1916.

The strontium minerals[1] are celestite ($SrSO_4$) and strontianite ($SrCO_3$). Both are mined for making salts that are used in the refining of sugar and the manufacture of fireworks and medicines. The principal salt used is strontium hydrate, which when added to beet molasses will cause the precipitation of strontium disucrate, from which a pure granulated sugar can be made.

Celestite occurs in crevices in limestones and associated with gypsum, calcite, and sulphur in sedimentary rocks. Rarely it is a gangue mineral in metalliferous veins. In Texas it is found in cavities of Cretaceous limestone.

A noteworthy occurrence is in the Avawatz Mountains, San Bernardino County, California,[2] where celestite beds associated with salt and gypsum are included in a series of steeply tilted sediments. Locally the celestite zone is 75 feet thick. It is associated with a salt bed which lies above it. Celestite associated with gypsum is found about 15 miles north of Gila Bend, Ariz.,[3] in a series of tilted sedimentary beds and lava flows.

Most of the celestite used in the United States is imported from England. It is mined at Yate,[4] about 10 miles northeast of Bristol.

The producing area at Yate is about 600 yards wide and 5 miles long. The celestite occurs as irregular masses and lenses localized along a definite horizon in Triassic marl; it occurs also in fissures in the underlying steeply dipping rocks on which the marl was unconformably deposited. The layers of celestite are locally as much as 3 feet thick but pinch out abruptly. Although not continuous, they appear again farther on at the same level. Gypsum occurs near the celestite masses but not in them.

The celestite is prospected by probing with a boring tool. If none is found to a depth of 9 feet, a new site is chosen. If celestite is found, a pit is dug and enlarged as the mineral is extracted. If the floor on which the marl rests is reached, a

[1] Pratt, J. H.: Strontium Ores. U. S. Geol. Survey *Mineral Resources*, 1901, pp. 955–958, 1902.

[2] Phalen, W. C.: Celestite Deposits in California and Arizona. U. S. Geol. Survey *Bull.* 540, pp. 521–533, 1912.

[3] Schrader, F. C.: *idem*, p. 351.

[4] Baker, B. A.: Celestite Deposits of the Bristol District. British Naturalists Soc. *Proc.*, vol. 9, p. 162, 1902.

Sherlock, R. L.: Celestite and Strontianite; Special Reports on Mineral Resources of Great Britain. England and Wales Geol. Survey *Mem.* vol. 3, pp. 41–54, 1915.

crowbar is used to find any celestite that may occur in cavities and bedding planes of the underlying rocks. One pit may yield several thousand tons; the next may yield very little. As stated by Sherlock about one-half the celestite obtained comes from the marl and the other half from the underlying rocks.

Strontianite is easier to treat than celestite and contains more strontium, hence it sells for a higher price. Only two regions are known where it is found in workable amounts. There are strontium hills near Barstow, California, and Muenster district, Westphalia, Prussia. In the Barstow region, as shown by Knopf,[1] strontianite partly replaces a fresh-water algal limestone of Miocene age. Strontianite and strontium-bearing rock have been found at a large number of places in a belt about 2 miles long. They occur as layers that lie parallel to the bedding of the inclosing clays and are distributed at intervals through a thickness of several hundred feet.

All the strontianite carries calcium carbonate, isomorphously intergrown with the strontium carbonate. Calcite is associated with witherite in places. Locally the strontianite is traversed by veins of celestite which are probably alteration products of strontianite. Knopf states that the strontianite deposits have been formed through the replacement of limestone by the agency of cold meteoric waters.

Fluorite and Cryolite.—Fluorite, or fluorspar (CaF_2), is a common mineral in vein deposits.[2] It is found in many districts as a gangue mineral of gold, silver, and zinc veins, but in these deposits in the United States it is not exploited. The chief source of fluorite is southern Illinois,[3] where lower Carboniferous beds are extensively faulted and intruded by lamprophyre dikes. The veins dip steeply and cut across beds of limestone. Some of them are nearly 40 feet wide; some solid masses are 10 feet thick. Some galena, sphalerite, pyrite, and chalcopyrite are associated with the fluorite. The gangue minerals are quartz and calcite, and in some of the veins barite is present. The

[1] KNOPF, ADOLPH: Strontianite Deposits near Barstow, California. U. S. Geol. Survey *Bull.* 660, pp. 257–270, 1918.

[2] BURCHARD, E. F.: Fluorspar and Cryolite. U. S. Geol. Survey *Mineral Resources*, 1907, part 2, pp. 637–641, 1908 (gives bibliography).

[3] BAIN, H. F.: Fluorite Deposits of Southern Illinois. U. S. Geol. Survey *Bull.* 255, 1905.

CURRIER, L. W.: Fluorspar, Lead and Zinc. Geology of Hardin County, Ill. Geol. Survey *Bull.* 41, pp. 247–310, 1920.

fluorite does not dissolve very readily from the outcrops and at some places is recovered by placer mining. At the Riley mine, Crittenden County, Kentucky,[1] fluorite ore fills a fault fissure between Carboniferous limestone and quartzite. Fluorite is found also in Boulder County and at Wagon Wheel Gap,[2] Colorado; at the latter place it is mined along a fissure from which hot springs now issue.

The principal use of fluorite is for flux. About 80 per cent. of the American output, according to Burchard, is used in the steel trade in the manufacture of open-hearth steel. Fluorite is used also in making aluminum, in the electrolytic refining of antimony and lead, and for manufacturing glass, enamel, and hydrofluoric acid. A clear variety of white fluorite is used for making certain optical apparatus. The production of fluorite in the United States in 1920 was 186,000 tons, valued at $4,544,000. It is in good demand.

Fluorite occurs in Ontario near Modoc, Hastings County and also in Huntington County. It is associated with lead-zinc ores in Carboniferous sedimentary rocks of Derbyshire and Durham, England where it is mined, and it is mined also in the Harz Mountains, the Black Forest, and Thuringia, Germany.

Cryolite (Na_3AlF_6) is a comparatively rare mineral. The principal deposits are at Ivigtut, in southern Greenland, where a wide vein in granite[3] carries, with much cryolite, a little siderite, quartz, pyrite, chalcopyrite, and sphalerite. Peripheral portions of the vein carry also feldspar, cassiterite, fluorite, and other minerals. A cryolite-quartz vein in granite occurs south of Pikes Peak, Colorado.[4] Cryolite imported from Greenland is used in making sodium salts, aluminum, glass, and enamel ware.

[1] Fohs, Julius: Fluorspar Deposits of Kentucky. Ky. Geol. Survey *Bull.* 9, 1907.

Miller, A. M.: The Lead- and Zinc-Bearing Rocks of Central Kentucky. Ky. Geol. Survey *Bull.* 2, pp. 1–35, 1905.

[2] Emmons, W. H. and Larsen, E. S.: The Hot Springs and Mineral Deposits of Wagon Wheel Gap, Colorado. *Econ. Geol.*, vol. 8, p. 242, 1913.

[3] Quale, Paul: An Account of the Cryolite of Greenland. Smithsonian Inst. *Rept.*, 1866, p. 398.

[4] Dana, J. D.: "System of Mineralogy," 6th ed., p. 167, 1892.

CHAPTER XVI

MISCELLANEOUS MINERALS

Natural Abrasives.—Many minerals and rocks are used in their natural state as abrasives. These include sandstone, grit, chert, garnet, corundum, emery, quartz, feldspar, infusorial (diatomaceous) earth, tripoli, pumice, etc.

Millstones are shaped from grit and sandstone. They are manufactured in several States, especially in New York and Virginia. Formerly they were in considerable demand, and in 1880[1] the production in the United States was valued at $200,000. In 1915, however, the total was only $53,480. In recent years the use of steel rolls and ball mills for grinding has caused a marked decrease in the demand for millstones.

Grindstones also are shaped from grit or sandstone. They are used mainly to sharpen steel tools. The grain should be fairly uniform and the particles cemented firmly, yet the pore spaces should not be entirely filled with cement so that cutting edges are buried. Too much clay in the sandstone will cause a smooth surface to form on grinding, and that will impair cutting efficiency. Certain layers of the Berea grit of Ohio and Michigan are extensively used for grindstones.

Pulpstones are large grindstones used for grinding wood to paper pulp. The wood is softened by introducing steam in a jacket around the circular pulpstone, and the pulpstone must have a cement that does not disintegrate in the presence of steam. Most of the pulpstones used in the United States come from England. Some of the stones are 5 feet or more in diameter and weigh over 2 tons. Experiments have been made to utilize sand and cement to make artificial pulpstones, so as to avoid the expense of shaping.

Scythestones, whetstones, and oilstones are small abrasive stones generally used as hand tools. They are made from rocks of varied character, but mainly from sandy sedimentary rocks and schists. The novaculite (hard) and Wachita (soft) stones

[1] PHALEN, W. C.: Abrasive Materials. U. S. Geol. Survey *Mineral Resources*, 1911, part 2, p. 837, 1912.

of southwestern Arkansas are noteworthy. Both of these stones are nearly pure silica. They are found as thin beds in a folded series of sandstones and shale. The hard Arkansas stone is very dense and has but small pore space; it is much prized as a finisher of razors and other fine instruments. The soft Arkansas stone has much greater abrasive power on account of its greater pore space, but it does not produce so fine an edge.

Volcanic "ash" is volcanic matter in a very finely divided state (Fig. 201). It is used for polishing and for making scouring soaps. It is common in many Western States and is mined in Nebraska.[1] Pumice is a solidified rock froth formed of rock material by gases escaping from lavas and having in general about the composition of rhyolite. It has many domestic uses. Ground pumice resembles volcanic ash. The pumice blocks of commerce come mainly from Lipari, an island north of Sicily. Deposits are known in the western part of the United States, but apparently they can not compete with those of Italy, where labor is cheaper.

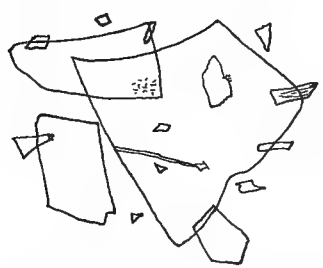


FIG. 201. — Volcanic ash from Beaverhead County, Montana. Greatly enlarged. (*After J. P. Rowe.*)

Garnet is extensively used as an abrasive, particularly the varieties almandine, pyrope, and grossularite. The garnets used for this purpose are obtained from schists in New York, New Hampshire, and North Carolina. Considerable garnet is used in the manufacture of sandpaper, and for certain purposes it is superior to quartz.

Corundum (Al_2O_3) is one of the hardest minerals, standing at 9 on the Mohs scale. Its powder is used for grinding, and small crystals are used for watch jewels. It is found in certain igneous rocks that are rich in aluminum and poor in silica. Corundum occurs also in nepheline syenite,[2] schist, and pegmatite and in gravel formed by the waste of corundum rocks. Corundum is found at many places in the crystalline schist belts of the Appa-

[1] BARBOUR, E. H.: Pumice. Neb. Geol. Survey, vol. 1, pp. 214–220, 1903.

[2] ADAMS, F. D.: On the Occurrence of a Large Area of Nephelin Syenite in the Township of Dungannon, Ontario. *Am. Jour. Sci.*, 3d ser., vol. 48, pp. 10–16, 1894.

lachian region. Pratt[1] has shown that some of the corundum ores are derived from dunite by segregation.

Emery is a mixture of hematite and corundum, and some of it contains other minerals. The ground powder is sized and used for polishing and for making sandpaper. It is mined in small quantities in the Appalachian region. Ground quartz also is used for making sandpaper.

Feldspar, which is softer than quartz, is ground and used for polishing powder, especially to polish glass and other materials where scratching is to be avoided. Diamonds are used as dust and, uncut, in bits of core drills. Chromic oxide and rouge (hematite powder) are used for fine polishing. The natural abrasives must compete more and more with the artificial abrasives, especially with carborundum (CSi) and alundum (Al_2O_3). Both of these are made in electric furnaces.

VALUE OF NATURAL ABRASIVES PRODUCED AND MARKETED IN THE UNITED STATES, 1918

Millstones	$ 61 676
Grindstones and pulpstones	1,707,004
Oilstones and scythestones	231,747
Emery and corundum	21,685
Garnet	434,425
Diatomaceous (infusorial) earth and tripoli	832,000
Pumice	114,433
Grinding pebbles and Tube-mill lining	77,823
Total	$2,864,332

Tripoli.—Tripoli is a porous siliceous rock that is found at many places in Illinois,[2] Missouri,[3] Oklahoma,[4] and Tennessee,[5]

[1] PRATT, J. H.: The Occurrence and Distribution of Corundum in the United States. U. S. Geol. Survey *Bull.* 180, p. 12, 1901.

[2] BAIN, H. F.: Analyses of Certain Silica Deposits. Ill. Geol. Survey *Bull.* 4, pp. 185–186, 1907.

[3] SIEBENTHAL, C. E., and MESLER, R. D.: Tripoli Deposits near Seneca, Mo. U. S. Geol. Survey *Bull.* 340, pp. 429–436, 1908.

[4] SHANNON, C. W.: The Resources of Oklahoma in a Pocket Book. Okla. Geol. Survey *Booklet*, pp. 1–62, 1912.

PERRY, E. S.: Tripoli Deposits of Oklahoma. Okla. Geol. Survey *Bull.* 28, pp. 1–32, 1917.

[5] GLENN, L. C.: A Tripoli Deposit near Butler, Tennessee. "Resources of Tennessee," vol. 4, No. 1, pp. 29–35, 1914.

and is used as an abrasive, as filler for surfaces that are to be painted, for stones through which to filter water, for blotter blocks, and for scouring stone. It is ground to fine dust or flour and used for polishing and in the manufacture of scouring soap. It is nearly pure silica (SiO_2), some analyses showing 98 per cent. A little alumina and iron are commonly present. It probably results from the decomposition of chert or the leaching of siliceous limestone. At Seneca, in Missouri, the deposits are found in the Boone formation, chiefly at the tops of hills. The bodies of tripoli are from 4 to 12 feet thick and rest on discolored tripoli or solid chert. Chert occurs also as balls and streaks through the body of the tripoli. Siebenthal and Mesler regard the tripoli as a product of leaching of siliceous limestone.

Mineral Paints.—Many mineral substances are used for pigments. The cheaper grades are generally fine clayey material highly colored with iron, manganese; or other minerals. In general they are residual products of the weathering of rocks containing these metals. Some earthy iron ore containing manganese is drab before and reddish brown after burning. Such material before burning is called "umber," and after burning "burnt umber." Sienna is a similar material, but of lighter color, probably due to hydrated iron oxide, limonite.

Ocher is the yellow iron oxide, limonite, incorporated in a clay base. Cinder from acid making (iron oxide), roasted siderite, and raw hematite are ground and used to make red paint. Black clay, shale, and slate are ground and used as fillers and as pigments. Some slates are distilled, and both the residue and the oil recovered are used in making paint. Calcium carbonate—limestone, calcite, and shells—is ground and used as "whiting." Slaked lime is used extensively for whitewash. Iron oxide, ground shales, and culm from coal washeries are used for mortar colors. Graphite, gypsum, asbestos, barite,[1] asphalt, and magnesite, discussed elsewhere, are all used as pigments. Much quartz or grit in paint is objectionable. The best test for the material is to grind it in oil and apply it to the surface to be painted. High-grade paints are made from compounds of lead, zinc, mercury, cobalt, arsenic, etc. The United States produced 57,442 short tons of natural pigments in 1915,[2] valued at $551,-

[1] Hill, J. M.: Mineral Paints. U. S. Geol. Survey *Mineral Resources*, 1912, part 2, pp. 955–984, 1913 (contains bibliography).

[2] Canvas discontinued after 1915.

598. More detailed information is given in reports of the United States Geological Survey.[1]

Pyrophyllite.—Pyrophyllite ($H_2Al_3Si_4O_{12}$), a hydrous aluminum silicate, resembles talc in that it is soft and easily worked. It is green when mined but dries white. When free from grit[2] it is used for some purposes similar to those for which talc is used. Pyrophyllite is used for sizing and bleaching cotton cloth, and it is claimed[3] by producers that the pyrophyllite mined in Moore County, North Carolina, is superior to talc for that purpose.

Glass Sand.—By weathering of rocks and transportation of the weathered material quartz is separated and accumulates along rivers, lakes, and seas. Where the sea bottoms are elevated, or where wind blows sand in dunes, the sands become more readily available. The washing by water and blowing about by winds are generally processes of purification, and some sands are nearly pure quartz, with about 99 per cent. silica and only 1 per cent. or less total alumina, lime, magnesium, and iron. Such pure sands are used for making glass. Sandstones and pure quartzites are likewise used. If more than a fraction of 1 per cent. of iron is present it may give the glass an undesirable color; magnesium renders the melt more difficultly fusible. Alumina introduced in clay tends to cloud the glass. Commonly some of the impurities are removed from sand by washing. Glass sands are widely distributed both geologically and geographically.[4]

[1] See particularly PHALEN, W. C.: Mineral Paints. U. S. Geol. Survey *Mineral Resources*, 1911, part 2, pp. 971–993, 1912 (contains an extensive bibliography).

BURCHARD, E. F.: Southern Red Hematite as an Ingredient of Metallic Paint. U. S. Geol. Survey *Bull.* 315, pp 430–434, 1906.

ECKEL, E. C.: The Mineral Paint Ores of Lehigh Gap, Pa. U. S. Geol. Survey *Bull.* 315, pp. 435–437, 1906.

HAYES, C. W.: Geologic Relations of the Iron Ores of the Cartersville district, Georgia. Am. Inst. Min. Eng. *Trans.*, vol. 30, pp. 415–418, 1900.

MILLER, B. L.: The Mineral Pigments of Pennsylvania. Pa. Topog. and Geol. Survey *Rept.* 4, pp. 101, 1911.

[2] PRATT, J. H.: Talc and Pyrophyllite Deposits in North Carolina. N. C. Geol. Survey *Econ. Paper*, No. 3, pp. 7–29, 1900.

[3] DILLER, J. S.: Talc and Soapstone. U. S. Geol. Survey *Mineral Resources*, 1911, part 2, p. 1197–1203, 1912.

[4] BURCHARD, E. F.: U. S. Geol. Survey *Mineral Resources*, 1911, part 2, p. 593, 1912. Glass Sand of the Middle Mississippi Basin. U. S. Geol. Survey *Bull.* 285, pp. 459–472, 1906. Glass-Sand Industry of Indiana,

In 1918 the United States produced 2,172,887 short tons of glass sand, valued at $4,209,728.

Infusorial (Diatomaceous) Earth.—Minute organisms such as diatoms and radiolaria—extract silica from water, and their tests accumulate in great abundance in some places at the bottoms of ponds, lakes, and in the sea (Fig. 202). This material when pure is very light and fluffy, and as it contains much air

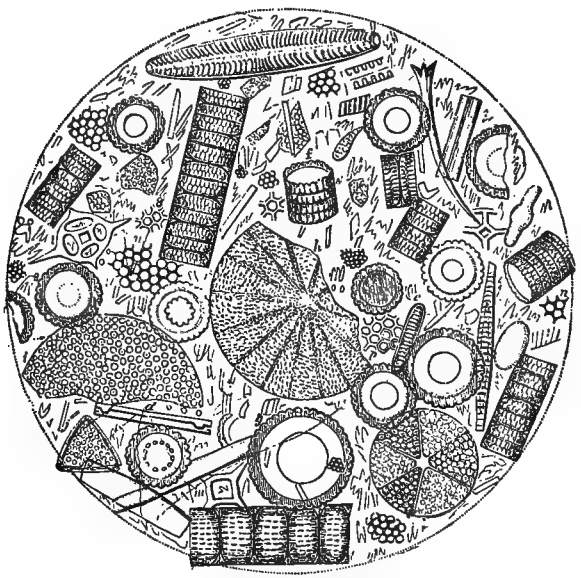


FIG. 202.—Infusorial earth, Richmond, Va., greatly enlarged. (*After Dana.*)

space it is an excellent nonconductor of heat. Diatomaceous earth is used for packing steam pipes, for polishing powder, as an absorbent for nitroglycerine, for making papier mâché, paper, sealing wax, glass, and in the preparation of pigments,

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Kentucky, and Ohio. U. S. Geol. Survey *Bull.* 315, pp. 361–376, 1907. Notes on Various Glass Sands, Mainly Undeveloped. *Idem*, pp. 377–382.

STOSE, G. W.: The Glass-Sand Industry in Eastern West Virginia. U. S. Geol. Survey *Bull.* 285, pp. 473–475, 1906.

FETTKE, C. R.: The Glass Sands of Pennsylvania. *Science*, new ser., vol. 48, pp. 98–100, 1918.

FETTKE, C. R.: Glass Sands. Am. Ceramic Soc. *Trans.*, vol. 19, pp. 160–194, 9 Figs., 1917.

BUTTRAM, FRANK: The Glass Sands of Oklahoma. Okla. Geol. Survey *Bull.* 10, pp. 1–91, 1913.

and for many other purposes. Its great abundance and various uses promise an increasing yield.[1] Generally some clay or fine sand occurs in the deposits, but the pure material is nearly pure silica. It is white, cream-colored, or light gray and is easily recognized under the microscope by the symmetrical boundaries of the constituent tests. Enormous deposits are found at Reno and Goldfield, Nevada, in Santa Barbara County California, and in Oregon. Diatom tests are abundant in the oil-bearing series of California, where the diatoms, according to Arnold and Anderson,[2] have contributed organic matter from which oil and gas have been derived. Diatom deposits are known also at Richmond, Va., and in Herkimer County, New York. In 1918 the United States produced infusorial earth valued[3] at $224,801.

Fuller's Earth.—Fuller's earth is a clayey material used for cleaning grease from cloth and for refining oils and other fluids by filtration. It removes objectionable color, odor, and turbidity from liquids and is used in refining olive oil and cotton oil, and in purifying petroleum for certain purposes. Like clay, it is a product of weathering or of weathering and sedimentation. It differs from clay, however, in that it has low plasticity. In color it ranges from gray to dark green. Its water content is high. Chemical analyses are of little aid in determining whether a clay will serve as fuller's earth. Tests for the purposes for which it is intended to be used give the only trustworthy evidence. Small tests are made by grinding the material in a coffee mill and filtering it in a Buchner funnel.

The demand for fuller's earth is good. The largest quantity is obtained in Florida and Georgia, where it is quarried from Oligocene beds. In Arkansas it is derived from weathered basic rocks. Shearer[4] says that the Fuller's earth of Georgia was deposited as a calcareous clay. The leaching out of the calcium carbonate left a large volume of openings, while the silica originally present, together with that deposited from solution, formed

[1] PHALEN, W. C.: U. S. Geol. Survey *Mineral Resources*, 1911, part 2, pp. 851–853, 1912.

[2] ARNOLD, RALPH, and ANDERSON, ROBERT: Diatomaceous Deposits of Northern Santa Barbara County, California. U. S. Geol. Survey *Bull.* 315, pp. 438–447, 1907.

[3] Includes rotten stone but excludes considerable diatomaceous earth used for special purposes not reported.

[4] SHEARER, H. K.: Bauxite and Fuller's Earth of Coastal Plain in Georgia. Geol. Survey of Georgia *Bull.* 31, p. 310, 1917.

a framework strong enough to hold the pores open. Papers treating deposits of fuller's earth in the United States are cited below.[1] The production of fuller's earth in the United States in 1920 was 128,487 tons, valued at $2,506,189.

Halloysite.—Halloysite ($Al_2O_3 \cdot 2SiO_2 \cdot 3H_2O$) contains one more molecule of combined water than kaolinite, and the elements seem to be less closely combined than in kaolins and ordinary clays. The alumina of halloysite is readily soluble in sulphuric acid. The mineral is used for making alum and other aluminum salts, as well as metallic aluminum.

Halloysite has been mined on the east slope of Taylor Ridge, 5 miles north of Gore, Ga., where, according to Shearer[2] there are probably several thousand feet of workings.

The halloysite is soft and waxy in appearance, with a pale greenish tint, and contains masses of harder brownish halloysite of flinty appearance but soft enough to be easily cut with a knife. Running through the halloysite masses are dendritic veinlets of black material, which consist largely of oxides of cobalt, nickel, and manganese.

The halloysite is overlain by massive chert and underlain plastic yellow clay. It occurs as irregular seams and pockets, just below the chert and often surrounding angular fragments of chert. The underlying yellow clay is locally sandy but contains no chert. The halloysite seams and pockets range from a few inches to several feet in thickness.

[1] ALDEN, W. C.: Fuller's Earth and Brick Clays near Clinton, Mass. U. S. Geol. Survey *Bull.* 430, pp. 402–404, 1910.

DAY, D. T.: The Occurrence of Fuller's Earth in the United States, Franklin Inst. *Jour.*, pp. 214–223, 1900.

MERRILL, G. P.: "The Nonmetallic Minerals," pp. 248–250, New York, 1904.

MISER, H. D.: Developed Deposits of Fuller's Earth in Arkansas. U. S. Geol. Survey *Bull.* 530, pp. 207–219, 1912.

PARSONS, C. L.: Fuller's Earth. U. S. Bureau of Mines *Bull.* 71, pp. 1–38, 1913.

PORTER, J. T.: Properties and Tests of Fuller's Earth. U. S. Geol. Survey *Bull.* 315, pp. 268–290, 1907.

RIES, HIENRICH: "Clays, Their Occurrence, Properties, and Uses," pp. 460–467, New York, 1906.

VAUGHAN, T. W.: Fuller's Earth of Florida and Georgia. U. S. Geol. Survey *Bull.* 213, pp. 392–399, 1903.

WESSON, DAVID: The Bleaching of Oils with Fuller's Earth. *Min. and Eng. World*, vol. 37, 1912, p. 667.

[2] SHEARER, H. K.: Bauxite and Fuller's Earth of the Coastal Plain of Georgia. Ga. Geol. Survey *Bull.* 31, pp. 330–332, 1917.

Lithographic Limestone.—Lithographic limestone is a dense, fine-grained, uniform limestone that is used for making lithographic plates.[1] It may be either calcium carbonate or dolomite. It should be free from veins and cracks and sufficiently absorbent to hold ink. Siliceous limestones are not satisfactory, for the stone must be soft enough to carve with the engraver's tool and must dissolve with acid evenly. Plates of zinc and aluminum are now used for many purposes for which lithographic limestone was formerly used. Practically all the lithographic stone used comes from Solenhofen, Bavaria. Satisfactory lithographic stone has been mined at Brandenburg, Meade County, Kentucky.

Iceland Spar.—Calcite ($CaCO_3$) is a mineral widely distributed in nature and formed under many conditions. It is rarely pure, however, for it generally contains magnesium, iron, or manganese. Pure crystalline calcite is known as Iceland spar and is used for optical purposes, particularly in the Nicol prism, and also for making standard solutions in the chemical laboratory. It is in demand and sells for a high price. The calcite from the quarry near Eskifjördhr, on the east coast of Iceland, is well known for its purity. The country is a plateau formed of volcanic rocks that are deeply entrenched by fjords. The opening,[2] in dolerite, is about 25 by 60 feet and 10 feet high. It was filled with closely fitting crystals 10 inches across that formed a compact mass. Minute crystals of stilbite cover surfaces of the calcite. The surrounding dolerite is traversed by small veinlets or ramifications of calcite which lead to the deposit. The waters now in the calcite body are not capable of depositing calcite, but, according to Hoskyns-Abrahall, they etch the mineral. Coarsely crystalline calcite, having a high grade of purity, is found also in Montana.[3]

Water.—Water (H_2O) is essential for animal and vegetable life, and it plays a part in the genesis of all minerals. A part of the rain water that falls upon the earth soaks into the ground and, where openings are available, re-issues as springs. The distribution and movements of ground water are mentioned under

[1] KUBEL, S. J.: Lithographic Stone. U. S. Geol. Survey *Mineral Resources*, 1900, pp. 869–873, 1901.

[2] HOSKYNS-ABRAHALL, J. L.: A Visit to the Calcite Quarry in Iceland. *Mineralog. Mag.*, vol. 9, p. 179, 1892.

[3] PARSONS, C. L.: Iceland Spar in Montana. *Science*, new ser., vol. 47, pp. 508–509, May 24, 1918. Abstract, *Min. and Sci. Press*, vol. 116, p. 824, June 15, 1918.

weathering and also in the discussion of the enrichment of ores. Nearly everywhere the ground contains some water, but the amount is exceedingly variable, depending on the climate, the structure of the rocks, the distribution of fissures, etc.

Below the vadose zone (page 247) the rocks are generally saturated with water. At greater depths, however, the rocks because of pressure are tight, and water if present is nearly static. Estimates of the amount of water in the earth's crust,[1] stated in terms of the thickness of a uniform blanket of water spread over the surface, range from less than 100 feet to nearly 1,000 feet.

Almost all deep mines encounter more or less water. Wells sunk for water frequently encounter a supply only a few feet below the surface. Some, however, go hundreds of feet to water, the depth depending on local conditions. On the flood plains of rivers, water is generally reached near the surface. Many wells in glacial drift encounter water at shallow depths. Some deep borings are dry.

Artesian Water.—Deep borings encountering abundant water supply are commonly termed artesian wells (from Artois, France, where wells of this sort have long been used). Originally, however, this term was applied only to flowing wells. The conditions that are favorable to the development of an artesian circulation are (1) a porous bed of size sufficient to serve as a carrier and reservoir, (2) an impervious bed above it, (3) a collecting area higher than the point of issue.[2]

Sandstones and gravels are good water carriers. The total pore space of such rocks commonly amounts to 10 per cent. or more. Because of their storage capacity thick sandstones are better carriers than thin sandstones. Fractured limestones or other fractured rocks may be reservoirs or carriers of water. Amygdaloidal lavas have high pore space and may carry water, but because their openings are not freely connected they are generally inferior to sandstones. The shafts that penetrate many tilted vesicular flows at copper mines of Keweenaw Point, Mich., are dry in the deeper levels.

[1] Van Hise, C. R.: A Treatise on Metamorphism. U. S. Geol. Survey *Mon.* 47, pp. 123–657, 1904.

Fuller, M. L.: The Amount of Free Water in the Earth's Crust. U. S. Geol. Survey *Water-Supply Paper* 160, pp. 59–72, 1906.

[2] Chamberlin, T. C.: Requisite and Qualifying Conditions of Artesian Wells. U. S. Geol. Survey *Fifth Ann. Rept.*, pp. 131–173, 1884.

For an artesian flow it is necessary that the pervious beds be capped by impervious or nearly impervious rocks (Fig. 203), for otherwise the water would escape and the water pressure would be lowered to a point where water would not rise in openings. In general shale forms the best cap above the pervious beds. The character of the rocks below the water carrier is not important if such rocks do not crop out below the carrier. If the underlying rocks are impervious they will hold the water in; if they are pervious and have no outlet they will be filled with stagnant water that will prevent the downward escape of water in the carrier. The water-bearing bed should be exposed at a point above the point of issue. The water will not rise as high as the point of entry because of loss of pressure due to friction.



A, A porous bed, lying between two impervious ones, outcrops on two sides of an artesian basin.



B, A porous bed between two impervious beds, thins out down dip. (*After T. C. Chamberlin, U. S. Geol. Survey.*)

FIG. 203.—Diagrams illustrating artesian conditions.

In crystalline rocks, such as granites and schists, where joints and fissures are numerous and closely spaced, these openings may serve as reservoirs of underground water. In general it is necessary to pump the water, and as a rule the flow is not great. In some mines in crystalline rocks, however, the flow of water is very large after numerous drifts and crosscuts have been run into the surrounding rocks. As a rule small pumps can handle the water encountered in sinking shafts in crystalline rocks, and unless master fissures are cut the amount per foot of opening, of water flowing to the shaft decreases a few hundred feet below the surface.[1]

Mineral Water.—Natural waters are rarely pure. Even rain water carries some mineral salts, as well as carbon dioxide and a little oxygen. Many minerals are attacked by water, and as rain water percolates through soil or rocks it gathers mineral matter, which it carries in solution.

[1] Discussions of the water supply of the United States are given in the water-supply papers of the United States Geological Survey.

Mineral waters are grouped as table and medicinal waters. Table waters are generally not high in mineral salts; if they were their taste and physiologic effects would render them unpopular. Waters low in mineral salts and high in carbonic acid are highly prized for table use because of the palatable quality imparted by the acid. Nearly all the carbonated waters of the trade are simply pure water or water of low salinity artificially carbonated. The United States in 1919 produced about 40,000,000 gallons of mineral waters valued at $5,000, 000.

Medicinal waters are prized because of their therapeutic qualities. Waters carrying less than 150 parts per million of total mineral matter are classed as "low in mineral matter,"[1] those carrying more than 500 parts are "high," and those carrying more than 2,000 parts are "very high." As a rule waters that contain more than 1,000 parts of salts per million are not palatable, yet waters with 2,500 parts per million may be used for many days without discomfort, and some persons can withstand waters with more than 3,300 parts per million. Waters with as much as 5,000 parts per million are inimical to health.

It has been questioned whether the mineral waters of some resorts possess the therapeutic effects that are ascribed to them. Some of these waters carry a mineral content lower than that of city supplies. Some of the "cures" reported to have been effected at these resorts are doubtless due to changes in the environment and manner of living of the patients and to copious drinking of water, which under some conditions is beneficial. Lithium salts are commonly supposed to relieve uric acid poisoning but this has been questioned. Sulphates in moderately large doses are cathartic. Magnesium carbonate and bicarbonate are alkaline and given in small doses will correct acidity of the stomach. Boron salts are antiseptic, and some barium salts are supposed to correct arterial troubles. Iron salts are tonic. Arsenic salts above small amounts are poison.

[1] Dole, R. B.: The Concentration of Mineral Water in Relation to Therapeutic Activity. U. S. Geol. Survey *Mineral Resources*, 1911, part 2, pp. 1175–1192, 1912.

CHAPTER XVII

IRON

Iron ores are widely distributed and are formed under many conditions. Iron is found in large amounts in many igneous rocks, some of which are rich iron ores. Some sedimentary rocks also are rich enough to mine for iron, and many rocks, sedimentary and igneous, upon weathering yield high-grade iron ores. Iron ores in the United States carry in general 35 to 65 per cent. of iron, and the larger portion of the iron ore now mined carries more than 40 per cent.

Mineral	Per cent. Fe	Composition
Limonite	59.8	$2Fe_2O_3 \cdot 3H_2O$
Hematite	70.0	Fe_2O_3
Magnetite	72.3	Fe_3O_4
Siderite	48.3	$FeCO_3$
Pyrite	46.6	FeS_2
Marcasite	46.6	FeS_2
Pyrrhotite	60.4	Fe_7S_8
Chamosite	47.0	Hydrous aluminum silicate of iron
Greenalite	25.0±	Hydrous silicate of iron
Ilmenite	36.8	$FeTiO_3$

IRON ORE MINED IN THE UNITED STATES, BY MINING DISTRICTS AND VARIETIES, 1918 LONG TONS[1]

District	1918			
	Hematite	Brown ore	Magnetite	Total
Lake Superior	59,779,794	.....	.....	59,779,794
Birmingham	4,763,057	344,332	.....	5,107,389
Chattanooga	516,259	309,268	.....	825,527
Adirondack	.....	.....	762,029	762,029
Northern New Jersey and southeastern New York	.....	.....	523,862	523,862
Other districts	835,599	960,244	863,834	2,659,677
	65,894,709	1,613,844	2,149,725	69,658,278

[1] Data for 1919 and 1920 are not available at time of writing.

Iron ore sells at $1 to $7 a ton. Bessemer ores, which contain little phosphorus, sell for more than non-Bessemer ore, because they are easier to treat.

Of the iron-bearing minerals hematite is by far the most important. At present it supplies over 90 per cent. of the iron ore mined in the United States; limonite, magnetite and siderite supply nearly all the remainder.

Genesis of Iron-ore Deposits.—The ores of iron are in the main syngenetic. Some valuable deposits, including those of the Kiruna district, Sweden, and some of the magnetites of the Adirondacks, New York, have been formed by magmatic segregation. A great many deposits in the United States are sedimentary. These include the Lake Superior hematites, the Clinton iron ores, the black-band carbonate ores, and the Tertiary ores of Texas. The rich hematites of Minas Geraes, Brazil, and the limonite-carbonate ores of Luxemburg, Lorraine, and of the Cleveland district, England, and many other regions are also sedimentary beds. Magnetite ores in several districts in Montana, Colorado, California, New Mexico, and Utah are of contact-metamorphic origin. Other deposits have been formed in the deep-vein zone.

Many of the hematite and limonite ores in the United States are weathered products of ferruginous carbonate or ferruginous silicate protores. Some limonite deposits are oxidation products of sulphide deposits—for example, the limonites of Ducktown, Tenn. (pages 246 and 427) and of the Gossan lead, Virginia. At some places in the West and in Mexico the gossan ores are rich enough in iron to be mined for flux.

All ferruginous materials in the presence of air and water tend to change to the hydrous oxide; a steel rail, an igneous rock, a sulphide ore, or a ferruginous sedimentary rock will all yield limonite. Oxidation or weathering almost invariably results in the concentration of iron near the surface (page 247). The materials other than iron are removed more rapidly than iron, and because of their removal the iron remains in a more concentrated state. Many deposits are valuable only after enrichment by weathering. Thus the Lake Superior iron-bearing formations are all of too low grade to work except where superficial alteration has taken place. Ores of the "lateritic" or residual type like those of Cuba (page 245) have resulted from the thorough decomposition and leaching of iron-rich igneous rocks, other abundant

constituents having been removed in part or altogether by long-continued action of air and water. Tropical conditions are favorable to residual concentration.

Not all iron deposits have been reconcentrated by weathering. Some of the largest and most valuable deposits of iron ore in the world are workable in their original state. Examples are some magnetites of New York and Pennsylvania, the rich magnetites of the Kiruna district, in Sweden, and the rich sedimentary hematite ores of Minas Geraes, in Brazil.

The Lake Superior ores have been formed mainly by weathering of sedimentary protores. Although iron migrates slowly under conditions of weathering, some iron is dissolved and precipitated. The cementation of fractures by iron oxide, the replacement of soluble carbonates, and the development of crusts, stalactites, and stalagmites of limonite, etc., attend the weathering of most ferruginous materials.

Under some conditions[1] great quantities of iron are transported in solution and deposited in swamps, in lakes, and in the sea. The iron is probably carried as ferrous acid carbonate. In the presence of decaying vegetation iron is reduced and tends to remain in the ferrous state. Ferrous salts are more soluble than ferric salts. From these iron may be precipitated by decarbonization, by oxidation or by other chemical processes, or through the action of minute organisms known as iron bacteria. Bog and lake iron deposits[2] are commonly produced by the weathering of iron-bearing rocks in moist countries, and locally such deposits are mined for iron.

Iron is not dissolved readily under arid conditions. Beds of salt and gypsum are commonly associated with shales and sandstones stained red with hematite. The soluble salts of iron are the ferrous salts rather than the ferric salts. In the absence of organic products that supply reducing agents the iron is likely to be oxidized to the insoluble ferric condition. Thus, in an arid region, the iron may remain as residuary masses, or if it is removed it may be transported mechanically as the ferric oxide rather than in solution as ferrous salt.

[1] HARDER, E. C.: Iron-depositing Bacteria and Their Geologic Relations. U. S. Geol. Survey *Prof. Paper* 113, 1919.

[2] DAKE, C. L.: The Formation and Distribution of Bog Iron Ore Deposits. Am. Inst. Min. Eng. *Trans.*, vol. 53, pp 106–115, 1915.

IRON ORE DEPOSITS OF EASTERN UNITED STATES

Lake Superior Region.—The iron ores are widely distributed in the United States (Fig. 204). The most productive deposits are those of the Lake Superior region.[1] These deposits are in long and relatively narrow belts, the so-called iron "ranges."

The ores are carried by rail to upper Lake ports and shipped by boats to lower Lake ports, from which they are distributed to iron furnaces. The positions of the principal districts and their ports are shown in Fig. 205.

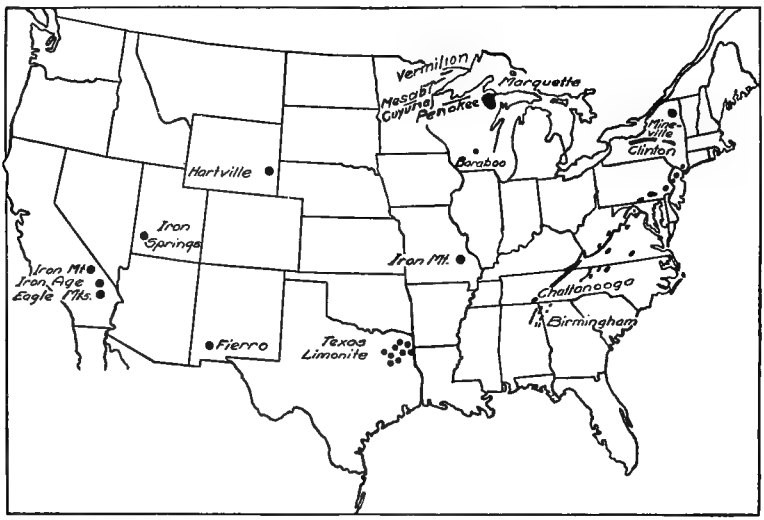


FIG. 204.—Outline map showing locations of the principal iron-ore deposits of the United States.

Practically all the ores mined in the Lake Superior region are superficially enriched products of pre-Cambrian sedimentary protores (Fig. 206). The principal iron-bearing formations are the Soudan (Keewatin), of the Vermilion range; the Negaunee (middle Huronian), of the Marquette range; and the upper Huronian or Animikie formations, of several other ranges. The upper Huronian is the most productive.

The iron-bearing formations are stratified sedimentary rocks composed chiefly of iron oxide, silica, iron carbonate, and iron silicates. Such rocks are called jasper, ferruginous chert,

[1] VAN HISE, C. R., and LEITH, C. K.: The Geology of the Lake Superior Region. U. S. Geol. Survey *Mon.* 52, p. 461, 1911.

taconite, greenalite, cherty iron carbonate, etc. By weathering and enrichment they become ore. The process is chiefly solution and removal of silica and carbon dioxide, although locally iron may be dissolved and precipitated as oxide by ground water.

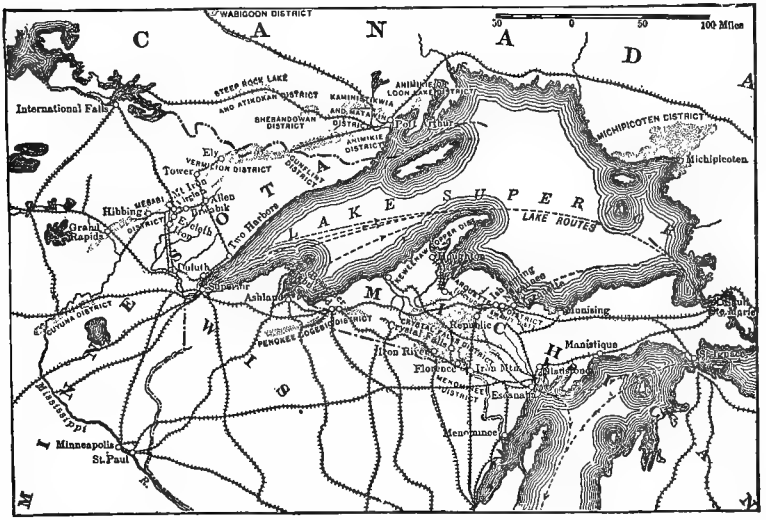


FIG. 205.—Sketch of Lake Superior region showing mining districts and ports. (*After Van Hise and Leith, U. S. Geol. Survey.*)

In all the ranges the iron-bearing formations have been tilted, and in some of them closely folded (Fig. 207). The ore-bearing formations have been exposed to weathering through many geologic periods. At some places removal of silica and con-

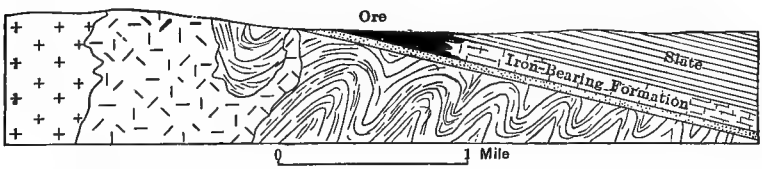


FIG. 206.—Cross-section of iron-ore deposit formed by leaching valueless material from a ferruginous sedimentary protore. (*Ideal section of Mesabi range, Minnesota, the drift covering is not shown.*)

centration of iron began in pre-Cambrian time. In the Vermilion range parts of the ore-bearing formation were weathered and metamorphosed to schists in the pre-Cambrian. In the Marquette district the Negaunee formation was altered by weathering

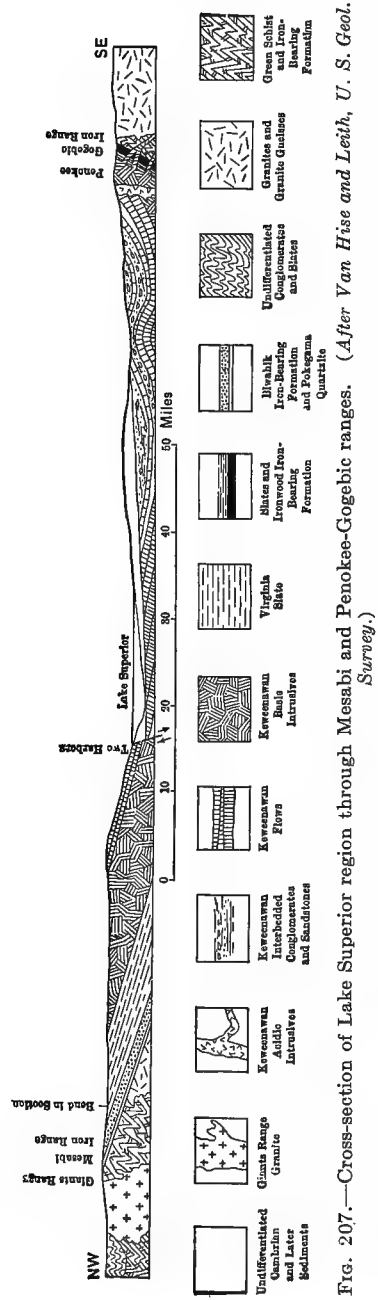


FIG. 207.—Cross-section of Lake Superior region through Mesabi and Penokee-Gogebic ranges. (*After Van Hise and Leith, U. S. Geol. Survey.*)

before upper Huronian time. All phases of the iron-bearing formation shown in this region, except specular hematite, had been formed, for they are represented by pebbles in the upper Huronian. The specular hematite was developed by deep-seated metamorphism of portions of the iron-bearing formation already weathered and enriched. This metamorphism, which gave a secondary cleavage to the iron ore, was accomplished by deformation that took place after the deposition of the upper Huronian sediments. In the Mesabi range concentration by weathering had taken place before the Cretaceous period, for pebbles of weathered ore are found in the conglomerate at the base of the Cretaceous. During long geologic ages large parts of the Lake Superior region have been land; for much of this time the land surface has been relatively low, a condition favoring extensive chemical denudation and deep weathering.

The weathered parts of the ore-bearing formations are found in various positions with respect to the geologic structure. On the Mesabi range the ore deposits are for the most part blankets that lie below the mantle of drift.

Here and there the ores extend down the dip of the beds below interstratified lean beds or below Virginia slate. Some of the deposits are due to leaching along enlarged joints.

In some of the iron ranges the rocks associated with the ores are complexly folded; the ores are in places found in pitching troughs where ground-water circulation has been controlled by impermeable beds or intrusive rocks, or by both. Circulating ground waters conducted along restricted paths through long periods have leached out silica to depths far below the surface. Locally also they have deposited iron oxide, cementing the ore and further enriching it.

Mesabi Range, Minnesota.—The iron deposits of the Mesabi range[1] are formed by local concentration in a ferruginous sedimentary formation, which extends from a point about 12 miles southwest of Pokegama Lake to Birch Lake, a distance of over 100 miles. The rocks strike about N. 73°E. and have low dips toward the south.

The rocks of the Algonkian system rest uncomformably upon the Archean rocks and are not so greatly metamorphosed. The oldest member of this system is a sedimentary series of conglomerates, graywackes, and slates, of lower-middle Huronian age which strike approximately with the axis of the range and stand nearly vertical.

The iron formation is of upper Huronian age. It rests unconformably on steeply dipping lower-middle Huronian and older rocks.

The upper Huronian is composed of (1) the Pokegama quartzite, consisting mainly of quartzite but containing also conglomerate at its base; (2) the Biwabik formation, which rests upon the Pokegama and consists of ferruginous cherts, iron ores, slates, greenalite rocks, and carbonate rocks, with a small amount of coarse detrital material at its base; and (3) the Virginia slate.

Some acidic and basic intrusive igneous rocks are associated

[1] WINCHELL, H. V.: The Mesabi Iron Range. Minn. Geol. and Nat. Hist. Survey *Twentieth Ann. Rept.*, pp. 111–180, 1893.

LEITH, C. K.: The Mesabi Iron-bearing District of Minnesota. U. S. Geol. Survey *Mon.* 43, 1903.

SPURR, J. E.: The Iron-bearing Rocks of the Mesabi Range in Minnesota. Minn. Geol. and Nat. Hist. Survey *Bull.* 10, pp. 1–268, 1894.

WOLFF, J. E.: Recent Geologic Developments on the Mesabi Iron Range, Minnesota. *Trans.* Am. Inst. Min. Eng., vol. 56, pp. 142–167, 1916; *Eng. and Min. Jour.*, July 17–Aug. 7, 1914.

with the upper Huronian sediments. All the upper Huronian rocks were formed after the close folding which affected the lower and middle Huronian sedimentary rocks. They dip at low angles (Fig. 208).

The Biwabik formation extends along the entire length of the range. Its thickness is about 620 feet, but owing to the prevailing low dips, the width exposed ranges from a quarter of a mile to 3 miles. The formation is generally covered with glacial drift, which ranges in thickness from 20 to 200 feet. Where it

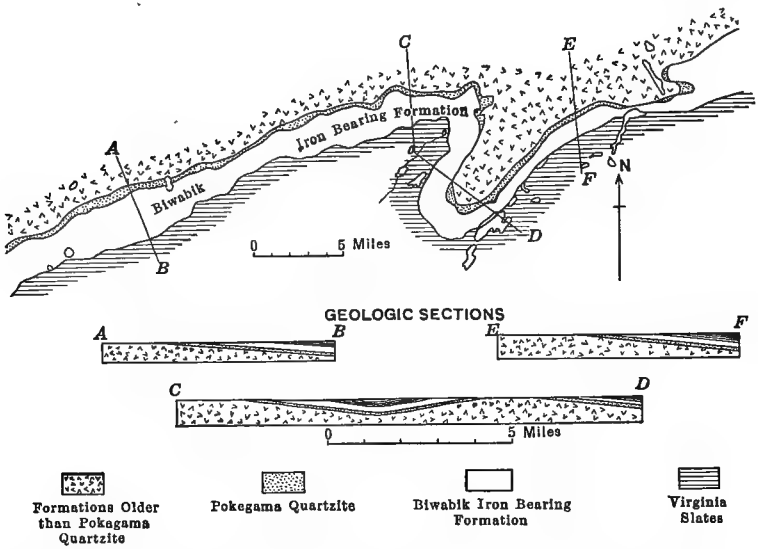


FIG. 208.—Map of central part of Mesabi range, Minnesota, with cross-sections. (*Based on map by C. K. Leith, U. S. Geol. Survey.*)

is not too thick the drift is removed by stripping, and the ore is loaded into cars with steam shovels.

The bulk of the Biwabik formation exposed is ferruginous chert, with which are varying amounts of amphibole, some lime and iron carbonate, and bands and irregular deposits of iron ore. Associated with the slaty layers in the iron-bearing formation or closely adjacent to the overlying Virginia slate are green rocks made up of small granules of a ferrous silicate called greenalite. The greenalite has at some localities been replaced by cherty quartz, magnetite, hematite, limonite, and other minerals, and associated with the greenalite rocks are small quantities of lime and iron carbonates.

At the east end of the range,[1] near Birch Lake, the iron-bearing formation has been metamorphosed to a rock composed of magnetite, amphibole, olivine, and quartz. There are large quantities of this material, which can be easily concentrated to a high-grade Bessemer product by magnetic concentration. In the future, as iron-ore reserves decrease, it will become an important economic asset.

The Biwabik formation may be subdivided into four members—from bottom to top: the lower cherty member, the lower slaty member, the upper cherty member, and the upper slaty member. The principal ore bodies are in the cherty members and in the lower slaty member.

The iron ores are formed by local concentration in the iron-bearing formation. This formation contains conglomerate and quartzite layers near the base and here and there thin layers of slate or other sedimentary rocks. The ferruginous layers grade laterally into slate bands, and upward the formation grades into the Virginia slate. The formation as a whole is extensive laterally and it has a comparatively uniform thickness like many other beds deposited in water.

Only small proportions of the Biwabik formation are rich enough to constitute iron ore. These are patches here and there along the eroded surface of the iron-bearing formation. The workable deposits are due to secondary concentration. The ore rarely extends to depths of more than 400 feet below the bedrock surface, although at some places it lies deeper.

Cuyuna Range, Minn.—The Cuyuna range,[2] southwest of the Mesabi range, extends from Aitkin through Deerwood and Brainerd to a point beyond Fort Ripley. It is about 65 miles long in a northeasterly direction and from 1 to 12 miles wide. This range was discovered by drilling areas showing magnetic attraction.

The iron-bearing formation occurs in eight or ten northeastward-trending, discontinuous belts. The dip of the beds is usually steep, and the prevailing dip is southeast. The forma-

[1] GROUT, F. F. and BRODERICK, T. M.: Report on the Magnetite Deposits of the Eastern Mesabi Range. Minn. Geol. Survey *Bull.* 17, pp. 1–58, 1919.

[2] HARDER, E. C. and JOHNSTON, A. W.: Preliminary Report on the Geology of East-central Minnesota, Including the Cuyuna Iron-ore District. Minn. Geol. Survey *Bull.* 15, 1917.

tion is inclosed between walls of sericitic, chloritic, or quartzose schist or slate. It consists mainly of ferruginous chert, but ferruginous slate is abundant, and in parts of the district magnetitic slate and amphibole-magnetite rock, are prominent.

The ore bodies are irregularly lens-shaped and lie within the iron-bearing layers; the longer diameter is usually parallel to the bedding of the iron-bearing formation. They may be inclosed within ferruginous chert or slate or other phases of the iron-bearing formation. Many of them are also bounded on one or both sides by schist or slate wall rocks. In places original iron-bearing rocks such as cherty and slaty iron carbonate have been encountered at varying depths below the ore and the associated altered phases of the iron-bearing formation. The ore contains much manganese oxide. Like iron, the manganese has been reconcentrated by weathering. Most of the ore bodies probably do not extend to depths of more than a few hundred feet below the bedrock surface (Fig. 209).

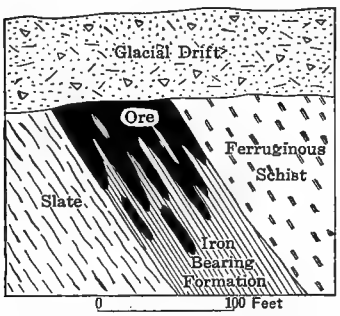


FIG. 209.—Cross-section of iron-ore deposit formed by leaching valueless material from a ferruginous sedimentary protore. (*Ideal section of Cuyuna range, Minnesota. After Harder and Johnston.*)

Penokee-Gogebic Range, Wisconsin and Michigan.—The Penokee-Gogebic range[1] is south of Lake Superior in northern Michigan and Wisconsin. The range trends N. 30° E. for about 80 miles. The principal mines are near Hurley, Wis., and near Ironwood, Wakefield, and Bessemer, Mich. (Fig. 210).

In a broad way, the iron-bearing rocks correspond to the Animikie iron-bearing series of the Mesabi range, Minnesota. The Ironwood formation corresponds in age and character to the Biwabik formation of the Mesabi range. It is succeeded by the Tyler slate, corresponding to the Virginia slate on the Mesabi range. On the Mesabi the ore-bearing series dip southeast at low angles; on the Penokee-Gogebic the series dip north or northwest at high angles. Low dips on the Mesabi favor the

[1] IRVING, R. D. and VAN HISE, C. R.: The Penokee Iron bearing Series of Michigan and Wisconsin. U. S. Geol. Survey *Mon.* 19, pp. 1–534, 1892.

development of the broad, shallow deposits that are worked by open cuts. Steep dips and narrower outcrops on the Penokee-

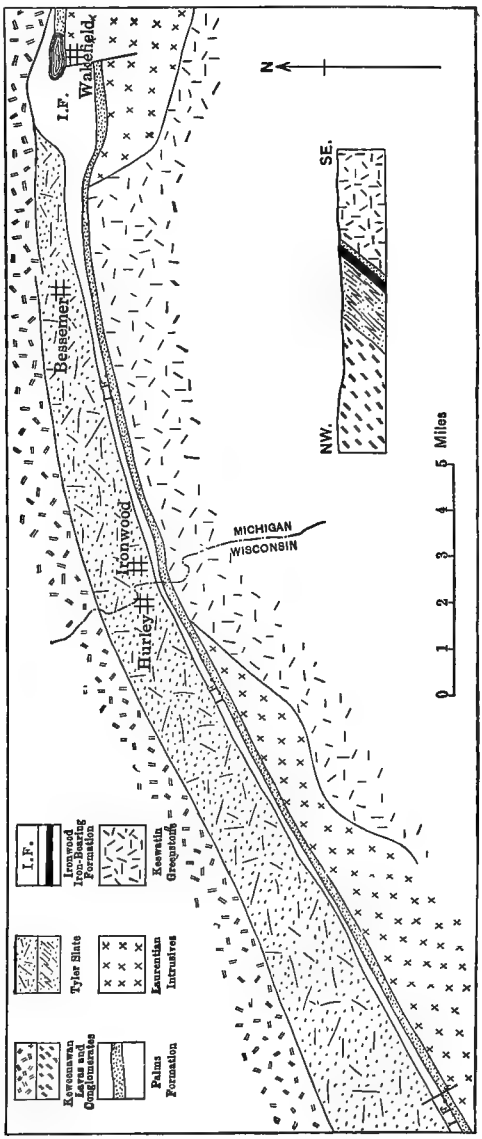


FIG. 210.—Sketch map of part of Penokee-Gogebic district, Wisconsin and Michigan with generalized cross-section. (*Based on map by Irving and Van Hise, U. S. Geol. Survey.*)

Gogebic range make it necessary to do the mining mainly underground. In both districts the sedimentary Animikie rocks have

a comparativey simple structure, but on the Penokee-Gogebic range they are intruded by many dikes, mainly basic in composition. The ore bodies are the portions of the Ironwood formation that have been enriched by surface agencies. Only a small area of the iron-bearing formation is workable, and the ores are found only in the central part of the range, in a belt about 26 miles long.

Oxidation extends to a depth of more than 2,000 feet. At that depth in the Newport mine the iron-bearing formation is as thoroughly oxidized and leached as it is near the surface. The downward circulation has been controlled by pitching troughs, and thus oxidation has been carried to extraordinary depths in channels where downward-moving waters concentrated. Some troughs are formed also by westward-pitching dikes inter-

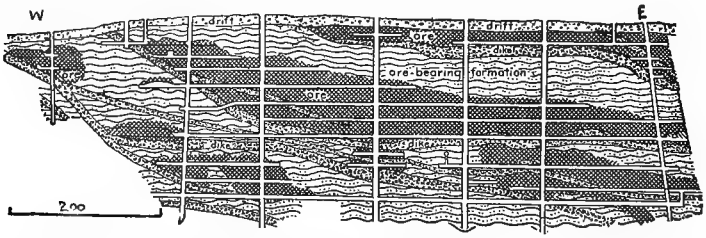


FIG. 211.—Longitudinal section of Ashland mine, Penokee-Gogebic district, Michigan. Shows ore bodies lying on dikes one above the other. (*After Van Hise and Leith, U. S. Geol. Survey from plate furnished by Olcott.*)

secting eastward-pitching dikes, and by dikes intersecting slate bands in the ore-bearing formation. These relations are shown by Fig. 211. Several ore bodies may be formed in troughs one below another.

Menominee District, Michigan.—The Menominee district[1] is in Michigan not far west of Escanaba, but outlying areas that may properly be included in this district are the Florence area,

[1] BAYLEY, W. S.: The Menominee Iron-bearing District of Michigan. U. S. Geol. Survey *Mon.* 46, 1904.

HOTCHKISS, W. O.: Mineral-land Classification of Wisconsin. Wis. Geol. and Nat. Hist. Survey *Bull.* 44, 1915.

ALLEN, R. C.: The Iron River Iron-bearing District of Michigan. Mich. Geol. and Biol. Survey *Pub.* 3, Geol. series 2, 1910.

CLEMENTS, J. M., and SMYTH, H. L.: The Crystal Falls Iron-bearing District of Michigan with a chapter on the Sturgeon River Tongue by W. S. BAYLEY. U. S. Geol. Survey *Mon.* 36, 1899.

in Wisconsin, and the Crystal Falls, Iron River, and Metropolitan areas, in Michigan.

The iron ores are in the Vulcan and Michigamme formations of the Animikie group. Greenalite and iron carbonate are not now present, but pseudomorphs of both are abundant.

The Vulcan formation and the overlying Michigamme slate are conformable, and the contact is usually sharp. The Michigamme formation is composed of black and gray slates, gray calcareous slates, graphitic slates, graywackes, thin beds of quartzite, local beds of ferruginous dolomite and siderite, and rarer bodies of ferruginous chert and iron oxide.

These formations that carry the ore deposits are closely folded. The larger deposits rest upon relatively impervious formations whose folds form pitching troughs (Fig. 212).

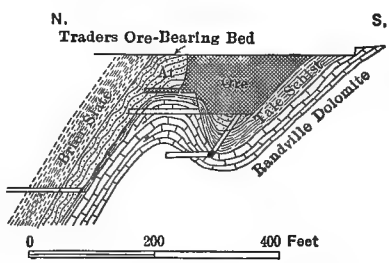


FIG. 212.—Vertical section through Norway-Aragon region, Menominee district, Michigan. Ore is developed in trough. (*After Bayley, U. S. Geol. Survey.*)

Marquette District, Michigan.[1]—The Marquette district extends from Marquette, Mich., on Lake Superior, westward nearly 40 miles, to Lake Michigamme. The principal towns in the district are Marquette, Ishpeming, Negaunee, Champion, and Republic. The outcrops of the Algonkian rocks range in width from about 1 mile to more than 6 miles.

The principal iron-bearing formation is the Negaunee (middle Huronian), but the Bijiki schist (upper Huronian) also is iron-bearing. The Goodrich quartzite, which overlies the Negaunee unconformably, includes a basal conglomerate, derived from the underlying Negaunee rocks, that locally contains iron ore. The Marquette district is structurally a synclinorium; the Negaunee formation is complexly folded so that it crops out over a large area, especially in the east end of the district (Fig. 213).

The protore in the Negaunee formation was originally iron carbonate and greenalite interbedded with more or less slate and

[1] VAN HISE, C. R., BAYLEY, W. S., and SMYTH, H. L.: The Marquette Iron-bearing District of Michigan. U. S. Geol. Survey *Mon.* 28, 1897.
VAN HISE, C. R., and LEITH, C. K.: The Geology of the Lake Superior Region. U. S. Geol. Survey *Mon.* 52, pp. 251–283, 1911.

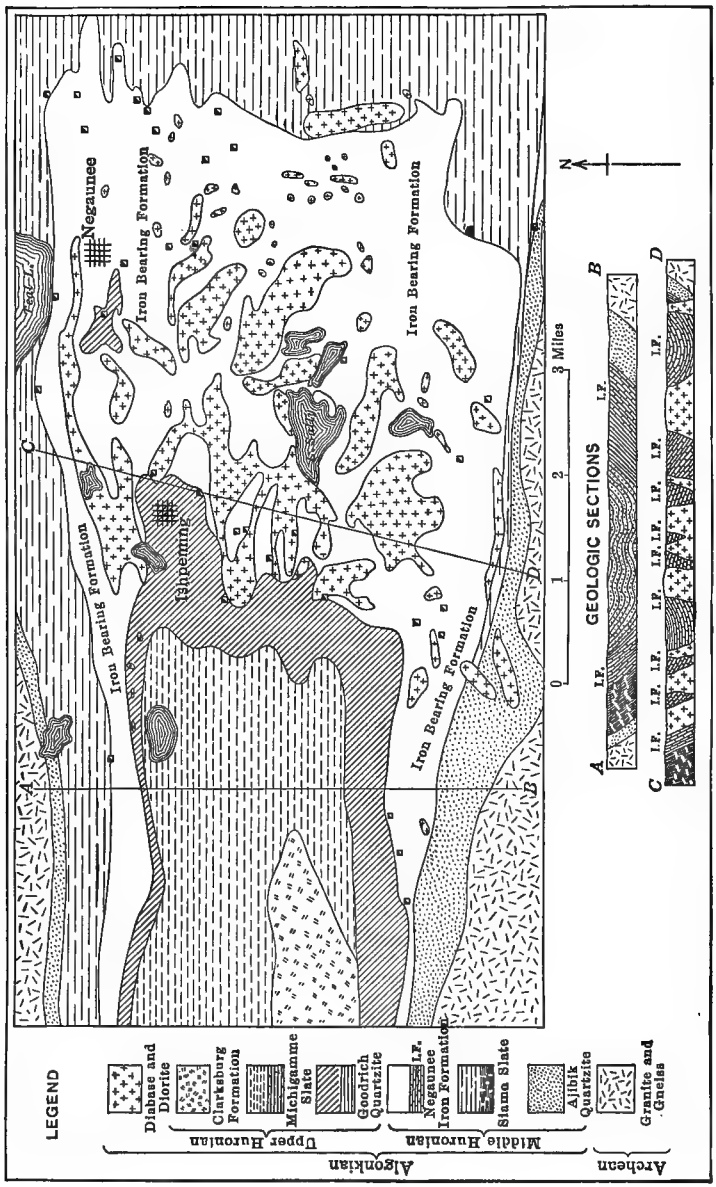


FIG. 213.—Map of part of Marquette district, Michigan. The map shows part of a synclinorium with axes pitching west, exposing a broad area of iron-bearing formation. (*Based on map by Van Hise and Bayley, U. S. Geol. Survey.*)

containing much detrital ferric oxide at the base of the formation. The alteration was accomplished by oxidation and hydration of the iron minerals in place, leaching of silica, and introduction of secondary iron oxide and iron carbonate dissolved from other parts of the formation. The flow of water concentrating the ore moved principally in planes parallel to the bedding and was especially effective in pitching troughs. The pitching troughs in this district are formed where a basic dike or boss cuts an impervious bed, where two igneous bodies are joined, or where an impervious bed is folded. Ores of the Negaunee formation are found near the base, in the middle zone of the formation, and near the top.

The ores of the lower and middle portions of the Negaunee are mainly soft, but the ores near the top are hard. The middle Huronian, including the Negaunee, was raised above sea level, weathered, and partly eroded before the upper Huronian sediments were deposited. The weathered Negaunee rocks near the ancient surface were doubtless enriched by the removal of material other than iron. After subsidence and deposition of the overlying upper Huronian, the rocks were metamorphosed and deformed by pressure. The enriched ores were thereby changed to specular hematite of high grade. In the iron-bearing formation of the middle and lower horizons of the Negaunee, silica and alkaline earths had not then been removed by weathering, and the rock was not oxidized during the early stage. The concentration of the iron at these horizons was brought about by surface waters at a later period, after the ores in the upper part of the formation had been rendered hard and schistose by dynamic agencies.

Vermilion Range, Minnesota.—The Vermilion Range,[1] in northeastern Minnesota, extends from a point near the west end of Vermilion Lake about 20° north of east to Gunflint Lake, on the Canadian boundary. It is about 100 miles long and from 5 to 15 miles wide.

The Ely greenstone is the oldest and the most extensive formation in this district. It consists mainly of altered, basic igneous

[1] WINCHELL, N. H., GRANT, U. S., and WINCHELL, H. V.: Minn. Geol. and Nat. Hist. Survey *Final Rept.*, vol. 4, 1898.

CLEMENTS, J. M.: The Vermilion Iron-bearing District of Minnesota. U. S. Geol. Survey *Mon.* 45, p. 463, 1903.

VAN HISE, C. R., and LEITH, C. K. The Geology of the Lake Superior Region. U. S. Geol. Survey *Mon.* 52, pp. 118–143, 1911.

rocks, probably in the main surface flows. At many places these rocks are highly schistose. The Soudan formation, which was deposited above the Ely greenstone, is the oldest iron-bearing formation in the district. It is made up chiefly of beds of jasper and contains also some slates and conglomerates. Some beds are composed largely of iron oxides or iron carbonates. The Ely greenstone and the Soudan formation are intruded by granite, felsite, and porphyries, which locally are metamorphosed to schists. These and the rocks they intrude were deformed and otherwise altered and in places were eroded before the sediments of the next system, the Algonkian, were deposited.

The lowest of the Algonkian rocks are of lower-middle Huronian age. The oldest member of this series is the Ogishke conglomerate. Above the Ogishke, in the eastern part of the district, is the Agawa formation, which contains beds of slate, jasper, iron oxides, and iron carbonates. This formation reaches a thickness of 50 feet and contains some unimportant iron ores.

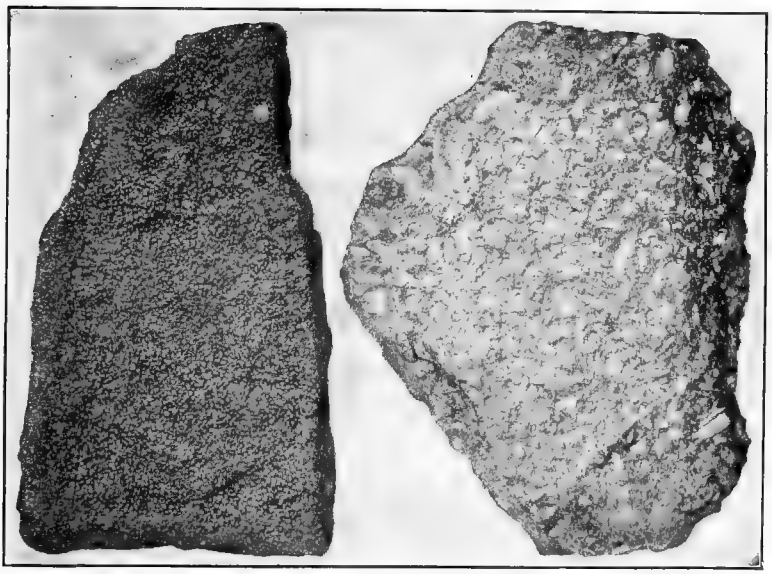
Above the Agawa is the Knife Lake slate, probably several thousand feet thick. The Knife Lake slate and older formations are intruded by the Giants Range, Snowbank, and Cacaquabic granites.

The upper Huronian rocks that contain the iron ores in the Mesabi range are of little value in the Vermilion district, although they occur in a small area west of Gunflint Lake.

The iron ores of the Vermilion range are almost exclusively in the Soudan formation and in places are 2,000 feet below the surface. Some concentration took place before the lower Huronian sediments were deposited, as is indicated by the fact that the lower Huronian conglomerates contain detrital iron ores. Close folding after the lower Huronian deposition rendered the ores hard, anhydrous, and crystalline. At Ely much concentration has taken place also since the deposition of the lower Huronian. Because the ore formations in the Vermilion district were closely folded after some concentration by ground water had taken place, the enriched ores are locally deep-lying.

Clinton Hematite Deposits.—Hematite deposits are found at many places along the outcrops of the Clinton (Silurian) formation from New York to Alabama but are workable only here and there. Valuable deposits of the Clinton type have been found in New York, Pennsylvania, Virginia, Tennessee, Georgia, Alabama and Wisconsin.

The deposits are lenses in sandstone and shale and occur at several horizons in the formation. At some places there are three or four beds, generally less than 10 feet thick, although some are much thicker. At Birmingham, Ala., the "Big seam" is 16 to 40 feet thick. Two types of ore are noteworthy—the fossil ore, made up of fossil fragments, mainly those of lime-secreting organisms replaced by iron oxide, and oolitic ore, made up of small spherules (Fig. 214). Some of the ore is soft and some is hard. The soft ores are the weathered parts of the seams;



Oolitic ore Fossil ore

FIG. 214.—Clinton iron ores from Clinton, N. Y. (*After Burchard, Butts and Eckel, U. S. Geol. Survey.*)

they form the outcrops and extend downward for varying distances. Below them the hard ore is found. The soft ore carries about 50 per. cent of iron and 12 per cent. of silica. The hard ore is of lower grade and carries more lime. Its composition is approximately as follows: Iron 35 per cent., silica 25 per cent., lime 20 per cent. By mixing hard and soft ores a self-fluxing furnace charge is obtained; thus the ores are cheaply beneficiated.

The reserves of the Clinton ores are large. In the Birmingham region 358,470,000 tons was estimated as available in 1909. In the region tributary to Chattanooga, Tenn., nearly 100,000,000

tons was estimated as available; in New York about 30,000,000 tons; and in Dodge County, Wisconsin, about the same tonnage as in New York. The structural conditions in these regions indicate that these estimates are low.

In the Birmingham district, Alabama,[1] the sedimentary rocks, including the Clinton beds, are folded and faulted, and the Clinton ores crop out as long, narrow strips striking northeast (Fig. 215). The section includes beds ranging from the Cambrian to Carboniferous, and because these beds are folded and eroded, their products, iron ore, coal, and limestone flux, are brought near together. The region, to use an engineering phrase, may be termed "self-contained," for all the materials necessary for the manufacture of steel are abundantly present within a radius of a few miles. The ores, though of lower grade than the Lake Superior hematites, can compete with them, because good coke is made in their vicinity and they command the Southern market for steel. They carry considerable phosphorus and are non-Bessemer. The development of the open-hearth process of steel making has greatly enhanced their value.

The principal fold in the district is an anticline, with a shallow syncline near its center: by the folding the outcrops of the Clinton ore are repeated, forming several parallel belts. The trend of the folds and therefore of the rock beds also is northeast.

The ore bodies dip with the rocks at moderately low angles. Where the ore beds are weathered, lime carbonate is dissolved out of them, thereby increasing the proportion of iron, silica, and other constituents. Such altered ore is termed "soft ore," for it is usually porous and friable, compared with the unaltered material, which is termed "hard ore." The alteration extends from the outcrop for distances of a few feet to 400 feet. The soft ore is generally more accessible and of higher grade than the hard ore, and in consequence much of it has already been mined.

The ores are sedimentary. Below the zone of surface leaching they extend thousands of feet without material change.

In eastern Tennessee, extending from Chattanooga northeastward across the State to Middleboro, Ky., and beyond, a distance of about 150 miles, Silurian beds crop out almost continuously. In this belt, which is practically in the strike of the Clinton beds

[1] BURCHARD, E. F., BUTTS, CHARLES and ECKEL, E. C.: Iron Ores, Fuels, and Fluxes of the Birmingham District, Alabama. U. S. Geol. Survey *Bull.* 400, 1910.

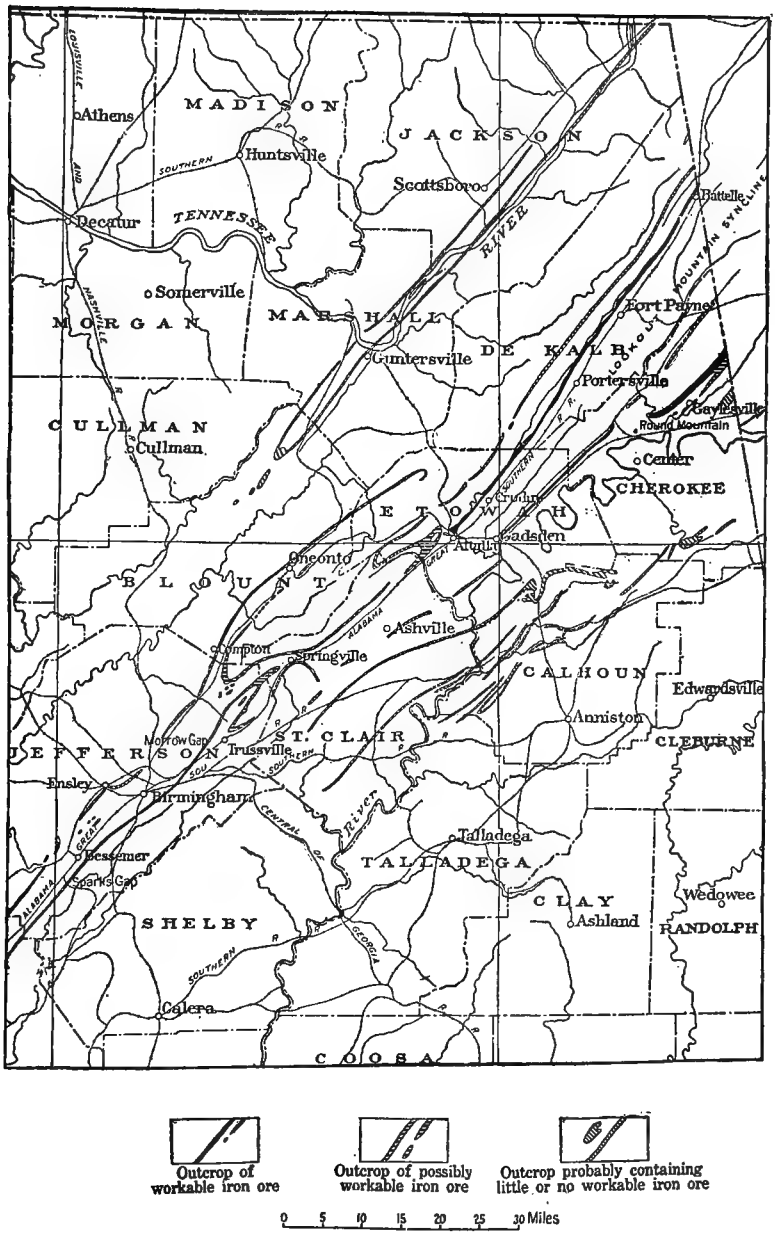


FIG. 215.—Map of region near Birmingham, Alabama. (*After Burchard, U. S. Geol. Survey.*)

of Birmingham,[1] Ala., and also in some outlying areas, there are valuable bodies of iron ore in the "Rockwood" formation,[2] which corresponds to the Clinton in Alabama and New York. The ore is of similar character and genesis.

The Clinton formation is extensively exposed in western and central New York.[3] Its outcrops are nearly parallel to the south shore of Lake Ontario, and the beds dip gently to the south. Developments are most extensive in Wayne County near Lake Ontario, but mines have also been opened near Clinton and elsewhere in central New York.[4] As in Alabama, the ores are fossiliferous or oolitic, and from one to four beds are known. Owing to the nearly flat dips the ores can be mined for considerable distances down the dip by stripping. The workable beds are thin, however, compared to those of Alabama.

Deposits of sedimentary iron ore of the Clinton type are found in Dodge County, Wisconsin.[5] They dip east at low angles, and their horizon is not more than 800 feet below the surface at Lake Michigan, 35 miles east of their outcrop. The ore beds vary in thickness, reaching a maximum of 55 feet. They have been followed 400 feet down the dip and are explored at greater depths by drilling.

The ore is hydrated iron oxide with 29 to 54 per cent. of iron and is high in phosphorus.

Magnetite Ores of Pennsylvania.—At Cornwall, Dillsburg, and several other places in eastern Pennsylvania,[6] large bodies

[1] SMYTH, C. H., JR.: "Types of Ore Deposits," pp. 33–52, 1911. See also *Am. Jour. Sci.*, 3d ser., vol. 43, pp. 487–496, 1892.

[2] BURCHARD, E. F.: The Red Iron Ores of East Tennessee. Tenn. Geol. Survey *Bull.* 16, p. 27, 1913.

GORDON, C. H.: Types of Iron-ore Deposits in Tennessee. "Resources of Tennessee," vol. 3, pp. 84–95, Tenn. Geol. Survey, 1913.

[3] NEWLAND, D. H. and HARTNAGEL, C. A.: Iron Ores of the Clinton Formation in New York State. N. Y. State Mus. *Bull.* 123, 1908.

[4] NEWLAND, D. H.: The Clinton Iron-ore Deposits of New York State. Am. Inst. Min. Eng. *Trans.*, vol. 40, pp. 165–183, 1910.

[5] CHAMBERLIN, T. C.: "Geology of Wisconsin," vol. 2, pp. 328–334, 1877.

VAN HISE, C. R., and LEITH, C. K.: The Geology of the Lake Superior Region. U. S. Geol. Survey *Mon.* 52, p. 567, 1913.

THWAITES, F. T.: Recent Discoveries of "Clinton" Iron Ore in Eastern Wisconsin. U. S. Geol. Survey *Bull.* 540, pp. 338–342, 1914.

[6] SPENCER, A. C.: Magnetite Deposits of the Cornwall Type in Pennsylvania. U. S. Geol. Survey *Bull.* 359, 1908.

HARDER, E. C.: Structure and Origin of the Magnetite Deposits of Dillsburg, Pa. *Econ. Geol.*, vol. 5, p. 599, 1910.

of magnetic iron ores are developed. The country is an area of sedimentary rocks, which are intruded by Triassic diabase and covered locally by basalt flows. The ores occur at the contact of the diabase with the sediments. The principal deposits lie along the northern edge of the Mesozoic Newark belt, where the diabase is intruded into limestones and limy shales of Cambro-Ordovician age. In places garnet, pyroxene, epidote, and other heavy silicates form the gangue of the magnetite ore. It is believed that the ores were deposited by solutions that emanated from the diabase and replaced the sedimentary rocks.

Magnetite Ores of New York and New Jersey.—In the Adirondack region, New York,[1] great deposits of magnetic non-titaniferous ores are associated with metamorphosed sediments and gneisses. The ores occur as rudely tabular bodies parallel to the general structure, though some are elongated and some irregular. They lie along the planes of foliation in the inclosing rocks. These ores are now mined on a large scale and concentrated.

In New Jersey magnetite iron ores which occur in gneisses are believed to be due to magmatic segregation.[2]

HEMATITES AND MAGNETITES OF WESTERN UNITED STATES

Hartville, Wyoming.—The Hartville iron-bearing district[3] is in the Hartville uplift, a mountain mass in east-central Wyoming.

The most valuable deposits are lenses of hematite that occur in schist on a limestone footwall. The ore largely replaces the schist, although in part it fills cavities in the schist which are due to jointing, faulting, and brecciation. Detrital ores of secondary derivation from these deposits are found in associated rocks later than the schist.

Hanover, New Mexico.—The Hanover (Fierro) district, New Mexico,[4] is 2 miles northwest of Santa Rita (Chino). Iron ores from the district are smelted at Pueblo, Colo. The rocks

[1] NEWLAND, D. H., and KEMP, J. F.: Geology of the Adirondack Magnetic Iron Ores. N. Y. State Mus. *Bull.* 119, 1908.

[2] BAYLEY, W. S.: Iron Mines and Mining in New Jersey. N. J. Geol. Survey *Final Rept.*, vol. 7, 1910.

[3] BALL, S. H.: The Hartville Iron-ore Range, Wyoming. U. S. Geol. Survey *Bull.* 315, p. 190, 1907.

[4] PAIGE, SIDNEY: The Hanover Iron-ore Deposits, New Mexico. U. S. Geol. Survey *Bull.* 380, p. 199, 1909.

LINDGREN, WALDEMAR, GRATON, L. C., and GORDON, C. H.: The Ore Deposits of New Mexico. U. S. Geol. Survey *Prof. Paper* 68, p. 313, 1910.

consist mainly of Carboniferous limestone, which is intruded by a stock of quartz diorite porphyry. Here and there along the contacts of the limestone with the porphyry thick garnet zones have been developed. These zones contain epidote, garnet, and augite, with quartz, calcite, pyrite, magnetite, and zinc blende.

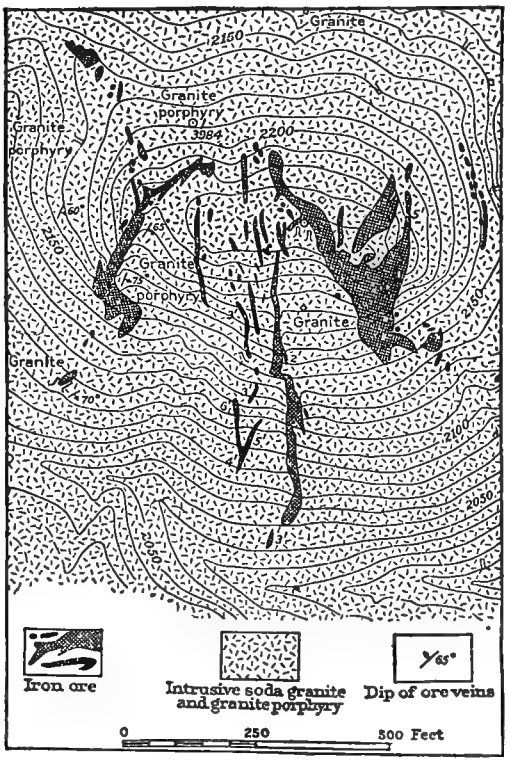


FIG. 216.—Map of Iron Age iron-ore deposits near Dale, Cal. (*After Harder and Rich, U. S. Geol. Survey.*)

The ores are arranged about the periphery of the intrusive, nearly everywhere practically at the contact. They are in the main irregular masses of magnetite, with some hematite.

Iron Springs, Utah.—Large deposits of magnetite are found in southwest Utah.[1] The ore replaces limestone near contacts

[1] LEITH, C. K., and HARDER, E. C.: The Iron Ores of the Iron Springs District, Southern Utah. U. S. Geol. Survey *Bull.* 338, 1908.

of igneous intrusives and fills fractures in the intrusies. Gangue minerals include garnet and other heavy silicates.

Eagle Mountain, California.—The Eagle Mountain region, California,[1] is an area of ancient gneiss, schist, and quartzite, upon which was deposited quartzite with lenses of dolomite. These rocks are intruded by great sills of monzonite.

The ores are irregular deposits formed through replacement of the limestone by solutions emanating from the igneous rocks. The ore is hematite, with some magnetite. A considerable proportion of it is very pure and of high grade, containing between 62 and 67 per cent. of iron and less than 0.06 per cent. of phosphorus. The principal gangue minerals are serpentine, mica, amphibole, garnet, epidote, pyroxene, and titanite.

Iron Age Deposit, Dale, Calif.—The Iron Age deposit is near Dale, San Bernardino County, California.[2] The country rock is an intrusive mass of soda granite and granite porphyry. The ores are chiefly hematite with subordinate magnetite and occur as veins cutting the intrusive granite and granite porphyry (Fig. 216). Garnet and epidote are locally associated with the ore and rocks. The principal iron-ore veins occur over an area about half a mile square; the larger veins, on account of their resistance to erosion, form the summit of a hill.

IRON MOUNTAIN AND PILOT KNOB, MO.

In St. Francis County, southeastern Missouri,[3] knobs of pre-Cambrian rocks, including porphyry, are surrounded by Cambrian sediments. At Iron Mountain and Pilot Knob considerable iron ore has been mined, the total production being nearly 6,000,000 tons. Iron Mountain was originally thickly covered with loose boulders of iron, and it was at first supposed that the entire hill was ore; but the mining operations disclosed the porphyry below the veneer of rich surface material.

The crest of the hill is a porphyry knob which is flanked by Cambrian sediments that rest unconformably upon the porphyry

[1] HARDER, E. C.: Iron-ore Deposits of the Eagle Mountains, California. U. S. Geol. Survey *Bull.* 503, 1912.

[2] HARDER, E. C., and RICH, J. L.: The Iron Age Iron-ore Deposit near Dale, San Bernardino County, Cal. U. S. Geol. Survey *Bull.* 430, p. 231, 1910.

[3] CRANE, G. W.: The Iron Ores of Missouri. Mo. Bureau of Geol. and Mines, vol. 10, 2d ser., pp. 107 *et seq.*, 1912.

and dip away from it. The ore occurs as huge irregular veins cutting the porphyry, as iron conglomerate at the base of the sedimentary series (Fig. 140, p. 231) and as residual boulders embedded in the clay that once covered the mountain. The veins are in places 60 feet wide and are the sources of the superficial boulder ore and of the conglomerate at the base of the Cambrian. The ore is hard hematite. Some magnetite is present, with quartz, tremolite, and apatite.

Pilot Knob, near Iron Mountain, is a small mass of porphyry almost surrounded by Cambrian sediments. The iron ore is a rudely tabular body which dips at low angles in the porphyritic rocks. Basal Cambrian conglomerates have accumulated near the deposits. These also are worked for iron ore. Boulder ore from the older deposits has accumulated at the present surface.

TITANIFEROUS IRON ORES

At many places in the United States there are large deposits of titaniferous magnetite ore.[1] These are not exploited at present, but if certain difficulties in smelting them are overcome they will probably be valuable. Most of these deposits have been formed by magmatic segregation.

Iron Mountain, Wyoming.—The region of Iron Mountain, southeastern Wyoming,[2] about 40 miles northwest of Cheyenne, contains huge deposits of titaniferous iron ore, which, however, are not exploited. The pre-Cambrian complex near the large dike of iron ore at Iron Mountain consists of anorthosite (essentially labradorite), the iron ore, and granite. The anorthosite is the oldest of these and is cut by dikes and lenticular masses of iron ore and granite. The deposit of iron ore is a dike 1¼ miles long and 40 to 300 feet wide. At several places it is cut by wedge-like masses of granite. The contact between the anorthosite and the ore, where exposed, is sharp, neither rock having notable gradational borders. The iron ore is a black holocrystalline igneous rock, whose constituent grains range from ⅛ to ½ inch

[1] Singewald, J. T., Jr.: The Titaniferous Iron Ore of the United States. U. S. Bur. Mines *Bull.* 64, 1913.

[2] Ball, S. H.: Titaniferous Iron Ore of Iron Mountain, Wyoming. U. S. Geol. Survey *Bull.* 315, p. 206, 1907.

Kemp, J. F.: A Brief Review of Titaniferous Magnetites. School of Mines *Quart.*, vol. 20, pp. 352–355, 1899.

in diameter. The greater portion of the iron ore is titaniferous magnetite but it contains also biotite, olivine, and feldspar.

SOME FOREIGN IRON ORE DEPOSITS

The six regions of the world that contain the largest reserves of iron ore probably are the Lake Superior district of the United States and Canada; Bell Island and Conception Bay, Newfoundland; eastern Cuba; the minette region of France, Luxemburg, and Belgium; Kiruna, Sweden; and Minas Geraes, Brazil.

The Lake Superior region of the United States has been decribed; the deposits are surface concentrations of pre-Cambrian

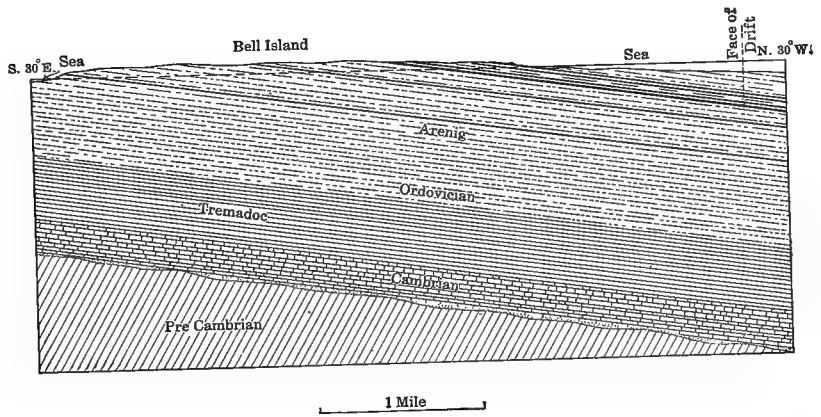


FIG. 217.—Section through Bell Island, Newfoundland. The dark lines are the ore beds. The main ore zone is the third from bottom. (*After Hayes.*)

sedimentary beds. There are considerable areas of the iron-bearing formations in Canada, but concentrations of high-grade ore are comparatively small.

In the Bell Island region, Newfoundland, the ores (Wabana[1] ores) are sedimentary beds interstratified with sands and shales of lower Ordovician age.[2] There are six beds of which three have been worked. The rocks dip about 10° N. W. (Fig. 217) and have been followed under the sea about 1½ miles from shore.

[1] Wabana is an Indian name signifying "place where daylight first appears," an appropriate name for the eastern part of the continent.

[2] HAYES, A. O.: Wabana Iron Ore of Newfoundland. Geol. Survey Canada *Mem.* 78, Geol. Series, 1915.

The Dominion bed is 35 feet thick and is composed mainly of ore. It is estimated that the district contains 3,250,000,000 tons of ore on Bell Island and within 5 miles of it. The ores are in part

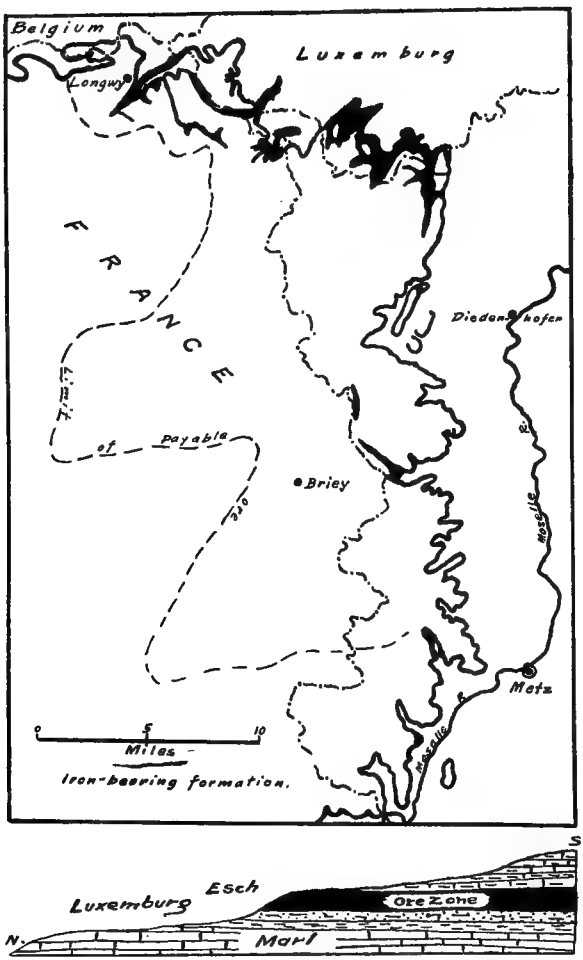


FIG. 218.—Map (upper) and cross section (lower) of Minette iron ore district of France, Luxemburg and Belgium. The beds dip west and south at a low angle as shown in the lower figure section. (*Based on data from Villaiu, Nicou, Branco and others.*)

oolitic and consist of hematite, chamosite (aluminous ferrous silicate), and siderite. They are high in phosphorus.

The iron ores of eastern Cuba[1] are the residual products of serpentine (p. 245). They lie near the surface, and the total reserves are estimated to be about 1,903,000,000 tons. The ore contains 40 to 50 per cent. iron, is high in moisture and low in phosphorus.

The minette ores of France[2] and Luxemburg (Fig. 218) are sedimentary beds in the Jurassic. They are almost flat-lying and cover a great area. Several beds 15 feet thick or less occur within a zone of 75 or 100 feet. They are associated with shales, sandstones, and marls. They contain 30 to 40 per cent. iron and are high in phosphorus. The reserves are estimated to be 5,000,000-000 tons.

At Kiruna,[3] northern Sweden, near the Arctic Circle, there is one of the largest deposits of magnetite known. This deposit (Fig. 219), is 2.8 kilometers long and about 150 meters wide, and

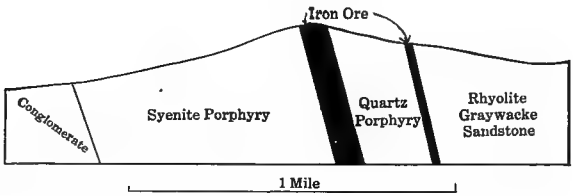


FIG. 219.—Cross section of magnetite iron ore deposits of Kiruna, Sweden. (*After Per Geijer.*)

contains over 1,000,000,000 tons of ore. The rocks and the deposit are of pre-Cambrian age. The associated rocks are greenstone, conglomerate, syenite porphyry, phyllites, graywacke, and sandstone. The principal deposit of magnetite lies between syenite porphyry and quartz porphyry (keratophyre). The ore

[1] CUMMINGS, W. L., and MILLER, B. J.: Characteristics and Origin of the Brown Iron Ores of Camaguey and Moa, Cuba. Am. Inst. Min. Eng. *Trans.*, vol. 42, pp. 116–137, 1911.

COX, J. S.: The Iron Ore Deposits of the Moa District, Island of Cuba. Am. Inst. Min. Eng. *Trans.*, vol. 42, pp. 73–90, 1911.

SPENCER, A. C.: Three Deposits of Iron Ore in Cuba. U. S. Geol. Survey *Bull.* 340, pp. 318–329, 1907.

[2] NICOU, P.: Les Ressources de la France en mineraisc le fer: "Iron-ore Resources of the World," vol. 1, pp. 1–39, Stockholm, 1910.

[3] LINDBOHM, H.: Abstract of Paper in *Zeitschr. prakt. Geologie*, vol. 6, pp. 423–426, 1898.

GEIJER, PER: Igneous Rocks and Iron Ores of Kirunavaara, Luossavaara, and Tuolluvaara.

is of high grade. It contains magnetite, a little hematite, considerable apatite, and some augite, biotite, titanite, and tourmaline. It is believed by some to have been formed in place by magmatic segregation. Others maintain that it is a dike which has been intruded from a magma that had segregated in depth. Other deposits of smaller size, yet very large, are found in this region.

The iron ores of the Minas Geraes region, Brazil, are in pre-Cambrian metamorphosed sedimentary rocks. The beds are practically pure hematite and are almost free from phosphorus. They are associated with ferruginous sandstone and quartzite and are believed to be of sedimentary origin. The ore is of exceptionally high grade, but the deposits have not been extensively exploited. Reserves are estimated to be 5,710,000,000 tons.

CHAPTER XVIII

COPPER

Mineral	Per cent. of copper	Composition
Brochantite	56.2	$Cu_4SO_4(OH)_6$ or $4CuO \cdot SO_3 \cdot 3H_2O$
Malachite	57.4	$Cu_2(OH)_2CO_3$ or $2CuO \cdot CO_2 \cdot H_2O$
Azurite	55.3	$Cu_3(OH)_2(CO_3)_2$ or $3CuO \cdot 2CO_2 \cdot H_2O$
Chrysocolla	36.0	$CuSiO_3 \cdot 2H_2O$ or $CuO \cdot SiO_2 \cdot 2H_2O$
Cuprite	88.8	Cu_2O
Tenorite	79.9	CuO
Chalcocite	79.8	Cu_2S
Covellite	66.5	CuS
Bornite	55.5	Cu_3FeS_3
Chalcopyrite	34.6	$CuFeS_2$ or $Cu_2S \cdot Fe_2S_3$
Enargite	48.3	Cu_3AsS_4 or $3Cu_2S \cdot As_2S_5$
Tetrahedrite	52.1	$Cu_8Sb_2S_7$ or $4Cu_2S \cdot Sb_2S_3$

Deposits of copper ores contain a greater variety of ore minerals than those of iron. Nearly all the minerals listed above are present as valuable constituents of copper deposits at one place or another. The principal ore minerals, however, are chalcocite, chalcopyrite, native copper, enargite, and their oxidation products.

The copper deposits of the United States are mainly epigenetic, thus differing from the larger iron deposits, which are in the main of syngenetic origin. Outside of the United States, however, there are valuable syngenetic copper deposits. The nickel ores of Sudbury, Ontario, which carry as much copper as some copper ores, were formed by magmatic segregation, and the famous copper deposits at Mansfeld, Germany, are probably of sedimentary origin. The great majority of copper deposits, however, the world over, are epigenetic (see Fig. 143, page 223).

Sulphide ores of copper are almost invariably leached near the surface except where the former surface material has been removed by rapid erosion or by glaciation. Many copper ores, however, contain other metals that are not so readily leached as

copper. Many valuable deposits of copper sulphide ore have been discovered by downward exploitation of oxidized gold and silver ores.

In regions where copper ores abound areas richly stained with iron are generally considered worthy of exploration in a search for copper. On the other hand, deposits of copper have been found below outcrops that show very little iron oxide. These outcrops, however, are generally silicified and kaolinized.

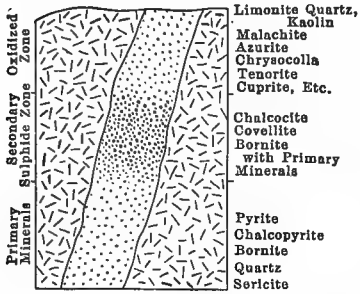


FIG. 220.—Ideal section showing distribution of ore minerals in a copper lode composed of chalcopyrite, bornite, pyrite, quartz, and sericite, after superficial alteration by weathering.

Most of the large copper sulphide deposits in the United States show three zones—a leached zone near the surface, an enriched zone below the leached zone, and a zone of lower-grade primary ore below the enriched zone (Fig. 220). In some deposits the oxidized ores and in some the primary sulphide ores are rich enough to work. In other deposits only the ores of the secondary sulphide zone are profitable.

In the oxidized zones of sulphide deposits the mineral waters are sulphuric acid and ferric sulphate solutions. Such solutions dissolve copper readily, and in contact with copper compounds such a system will contain also copper sulphate. The copper sulphate in solution reacts with carbonates or with acid carbonate in solution, precipitating copper carbonates. The sulphates chalcanthite and brochantite also may be precipitated. The silicates of copper are probably formed by copper-bearing solutions reacting on silicic acid, which is commonly present in mine waters. Native copper, cuprite, and tenorite are formed by the reduction or oxidation of various copper compounds. All these minerals are formed in the main in the oxidized zone, and in sulphide ore deposits their occurrence below this zone is exceptional.

Below the oxidized zone, where air is excluded, copper is precipitated as sulphides: chalcocite, covellite, bornite, chalcopyrite, and possibly some of the more complex antimony and arsenic compounds are formed by these processes. Precipita-

tion may be brought about by chemical interchange with pyrite, chalcopyrite, pyrrhotite, zinc blende, and galena, the process being mainly replacement. The copper sulphides are precipitated also by hydrogen sulphide, which is generated by attack of acid solutions on several of these sulphides. In a reducing environment the copper sulphides are highly stable. In pyrrhotite ores chalcocite enrichment is shallow. In deposits of sphaleritic copper ores without pyrrhotite the chalcocite zone may be moderately extensive vertically. The most extensive chalcocite zones are in pyrite and chalcopyrite deposits that do not contain pyrrhotite.

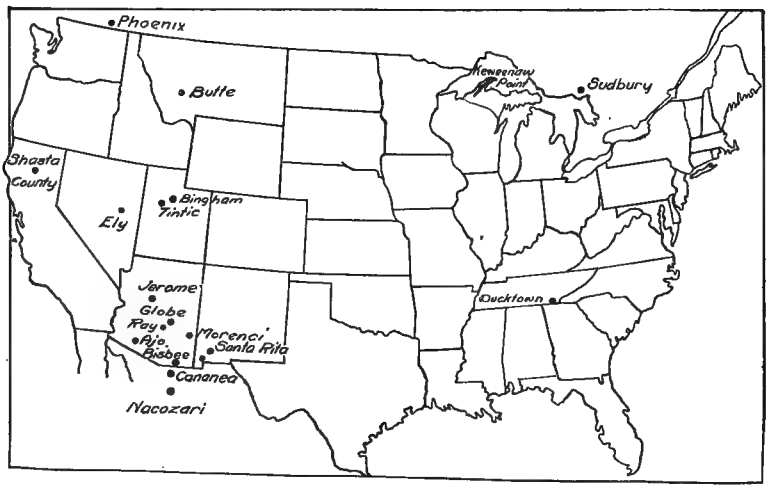


FIG. 221.—Sketch showing principal copper bearing districts in United States and some in Canada and Mexico.

Carbonates react with acid solutions and tend to delay the downward migration of copper. If there is much lime carbonate in the gangue of the ore or in the wall rock, the downward migration of metallic sulphates may be checked. Native copper is a common alteration product of copper sulphide ores. The zeolitic native copper ores of the Lake Superior region, however, are primary.

The uses of copper are well known. The production in the United States in 1920 was 1,209,061,040 pounds, valued at $222,467,000. Since 1918, production and prices have greatly declined. The principal districts in the United States are shown in Fig. 221.

Butte, Montana.—The Butte district, in western Montana, is the most productive copper district in the world. It has yielded over 8,000,000,000 pounds of copper, more than 400,000,000 ounces of silver, and 2,000,000 ounces of gold, also much zinc and smaller amounts of arsenic, lead and manganese. Developments extend to depths greater than 3,400 feet, where ores of good grade are found. The copper ore is concentrated or smelted directly in the great plants at Anaconda, Great Falls, and Butte.

The Butte district[1] is an area of quartz monzonite (frequently called granite), which is intruded by a later aplite, and by rhyolite porphyry. Dikes of late Tertiary rhyolite cut the granite, and effusive rhyolite rests upon it. In the western part of the region are Tertiary lake beds more recent than the granite rocks. These are composed of sand, gravel, and water-laid tuff.

The quartz monzonite, aplite, and porphyry, which contain all the ores, are phases of the great Boulder batholith,[2] which extends some 64 miles southward from a point near Helena and is 12 to 16 miles wide. This batholith intrudes Paleozoic and Cretaceous sedimentary rocks and along its borders has induced contact metamorphism by which garnet zones have been developed in the sediments. There are, however, no metamorphosed sediments in the Butte mining district.

There seems to be a genetic relation between the copper ores and the porphyry intrusives. The porphyry is found mainly in the eastern portion of the copper area, where it is younger than the Butte quartz monzonite and older than the veins, for even the oldest veins cut through it.

The copper ores are included in an area about 1½ miles long and a mile wide, and this area is almost surrounded by a much

[1] Weed, W. H.: Geology and Ore Deposits of the Butte District, Montana. U. S. Geol. Survey *Prof. Paper* 74, 1912.

Sales, R. H.: Ore Deposits of Butte, Montana. Am. Inst. Min. Eng. *Trans.*, vol. 46, pp. 3–106, 1914.

Simpson, J. F.: The Relation of Copper to Pyrite in the Lean Copper Ores of Butte, Montana. *Econ. Geol.*, vol. 3, pp. 628–636, 1908.

Kirk, C. T.: Conditions of Mineralization in the Copper Veins at Butte, Montana. *Econ. Geol.*, vol. 7, pp. 35–82, 1912.

Ray, J. C.: Paragenesis of the Ore Minerals in the Butte District, Montana. *Econ. Geol.*, vol. 9, pp. 463–481, 1914.

[2] Billingsley, Paul, and Grimes, J. A.: Ore Deposits of the Boulder Batholith of Montana. Am. Inst. Min. Eng. *Trans.*, vol. 58, pp. 284–361 (with discussion by W. E. Gaby, J. B. Hastings, and the authors, pp. 362–368), 1918.



FIG. 222.—Horizontal section of part of Butte district, Montana, 4,600 feet above sea level and about 1,500 feet below the surface. (*After Sales.*)

larger area containing closely spaced silver-bearing veins. Pronounced parallelism is noticeable in veins of both groups.

The fissuring in the district is exceedingly complex (Fig. 222). The systems as outlined by Sales are (1) Anaconda system; (2) Blue system of fault fissures; (3) Mountain View breccia faults; (4) Steward system; (5) Rarus fault; (6) Middle faults; (7) Continental fault.

1. The Anaconda system is composed of easterly fissures which are generally heavily mineralized and along which there has been but little displacement. In general they dip south at high angles. In the copper-producing area there are two notable groups of veins belonging to the Anaconda system. On the south or Anaconda group are the deposits of the Gagnon, Original, Parrot, Never Sweat, Anaconda, St. Lawrence, Mountain View, Leonard, West Colusa, and other mines. North of this group is the one which includes the Syndicate, Bell, Speculator, and associated deposits. Some of the easterly fractures are joined by many closely spaced smaller fractures, doubtless of the same age. They form altogether a network having what Sales has designated "horsetail" structure. In some mines the most valuable ore bodies are along these northwesterly conjugated fractures.

North of the copper-bearing area are the great easterly silver and zinc lodes. These also are believed to belong to the Anaconda system of fissures.

2. The Blue system is composed of several fissures that strike northwest. These cross and fault the veins of the Anaconda system. The lodes of the Blue vein system carry large deposits, although they are much less valuable and less uniformly mineralized than the easterly veins, on which the deposits are almost continuous except where displaced by faults.

3. The Mountain View breccia faults, which are later than the Blue Vein system, strike about N. 75° E. Near veins they contain locally enough brecciated ore to be worked.

4. The Steward system includes fault fissures that strike about N. 65° E. and extend across the Butte district. A few of them carry drag ore.

5. The Rarus fault is a complex fissure that is later than the mineralized faults. It is a crushed zone 20 to 250 feet wide and contains drag ore.

6. The Middle faults are later than the Rarus. They are not metallized.

7. The Continental fault, on the east edge of the mineralized area, is likewise later than the metallization of the district.

The rhyolite intrusion of Butte was subsequent to the earlier vein fissures; the silver veins are cut off by intrusive dikes of rhyolite.

Hydrothermal alteration of the quartz monzonite is extensive. Where large veins are closely spaced the entire area of quartz monzonite is hydrothermally altered; where the veins are less closely spaced fresh rock is found between them. C. T. Kirk recognized two phases of alteration—an earlier chloritic phase and a later sericitic phase.

The veins are replacement deposits, and, according to Sales, 60 to 80 per cent. of the ore is altered quartz monzonite with disseminated sulphides. The ores are of three classes—copper, siliceous silver, and zinc.

Chalcocite, enargite, and bornite are the most common copper minerals. Covellite occurs in large amounts in the Leonard mine, and chalcopyrite is present in workable quantities in a few properties. Pyrite is the most common sulphide.

Native silver occurs in the copper ores, especially in those from the upper levels. Ruby silver and black sulphantimonites and sulpharsenides occur in the siliceous silver ores. Free gold is rare. The gangue minerals include quartz, sericite, and several residual minerals of the altered country rock. Much rhodonite and rhodochrosite and some fluorite occur in the silver and zinc ores.

Sales states that there is a central zone of copper ore, mainly chalcocite and enargite, which grades into an intermediate zone that contains ores with the same minerals and also sphalerite, rhodochrosite, and rhodonite, with a slight increase of silver content. In an outer or peripheral zone the ores carry sphalerite, rhodonite, rhodochrosite, tetrahedrite, tennantite, and chalcopyrite, but rarely chalcocite or bornite. Their chief metals are silver, gold, zinc, and some lead.

Some silver lodes crop out conspicuously, but the outcrops of copper lodes are not prominent. The leached zone extends downward in places 300 or 400 feet below the surface. It contains silver, locally 30 ounces or more to the ton, but little copper. Below the oxidized zones of copper lodes, grading into them locally within 2 or 3 feet, are enormous masses of chalcocite, with some bornite and covellite.

In the great ore bodies of the upper levels of the Anaconda

vein chalcocite occurred in nearly pure masses 20 feet or more wide. In depth the mineral shows a more crystalline structure, and it is found in all the mines in greater or less abundance and purity, but as a rule it forms small grains scattered through the ores. The chalcocite ores are present in large quantities also between the 2,000- and 3,400-foot levels.

Investigators who studied the copper lodes in the earlier stages of their development regarded the chalcocite ores as secondary deposits formed by descending waters. More recent investigations, including those of R. H. Sales and associates, have shown that the deeper chalcocite ores are primary.

Bingham, Utah.—The Bingham district,[1] Utah, is in the Oquirrh Range about 20 miles southwest of Salt Lake City. Its measured reserves of copper ore are probably the largest in the United States. It has produced also large amounts of silver, lead, and gold.

The Bingham district is an area of Carboniferous quartzites and limestones intruded by monzonite and monzonitic porphyry and covered in part by andesites, andesitic porphyries, and breccias. The quartzite series ("Bingham quartzite") is several thousand feet thick. It contains at least seven limestone lenses, some of them 300 feet thick.

The region is crossed by many faults and fissures which trend in all directions. The faults are both normal and reverse, and some carry ore. Extensive fissuring and some faulting has taken place also after the deposition of the ores.

The ore deposits are in or near the intrusive monzonite or monzonitic porphyry. They include fissure veins in several formations, bedding-plane replacement deposits in limestone, and disseminated deposits in shattered porphyry.

The ore bodies that were most productive in the earlier history of the district are large replacement deposits of sulphide ore in limestone. These ores consist chiefly of pyrite, chalcopyrite, sphalerite, and chalcocite and their oxidation products. Pyrrhotite and a little garnet occur in some of the ores.

The ores of the Highland Boy mine near the surface were extensively oxidized and carried concentrated gold. The mine

[1] Boutwell, J. M.: Economic Geology of the Bingham Mining District, Utah. U. S. Geol. Survey *Prof. Paper* 38, 1905.

Beeson, J. J.: The Disseminated Copper Ores of Bingham Canyon, Utah. Am. Inst. Min. Eng. *Trans.* vol. 54, pp. 356–401, 1916.

was first exploited for gold, but deeper developments disclosed great bodies of copper ore containing gold and silver. The copper ores carry little chalcocite and are in the main primary. Other large deposits in this region carry lead and silver.

The argentiferous lead ores are deposits of galena that generally carry a high content of silver. They occupy veins in igneous and sedimentary rocks and replace limestone.

The largest deposit in the Bingham district is that of the Utah Copper Co. It covers an area of 211 acres, has an average thickness of 414 feet, and contains 338,000,000 tons of ore which carries 1.4 per cent. of copper (Fig. 154, p. 248). It lies like a thick blanket, covered by a mantle of rock leached of copper which averages 110 feet in thickness. This mantle rock is removed, and the ore is then mined with steam shovels. The ore is disseminated in shattered sericitized porphyry. The principal minerals are chalcopyrite, chalcocite, and covellite which appear as shots and stringers. The ore has been enriched by descending waters, which dissolved the copper from the mantle and from the overlying porphyry that has since been eroded, and deposited it below replacing the chalcopyrite and pyrite of the low-grade porphyry.

Ely, Nevada.—The Ely[1] (Robinson) district, in eastern Nevada, is an area of Paleozoic shales and limestones which are intruded by monzonite porphyry and locally are overlain by Tertiary rhyolite. The sedimentary rocks near the porphyry intrusions are locally garnetized or changed to jasperoid and commonly charged with great quantities of pyrite. In places near the igneous masses considerable amounts of chalcopyrite occur with the pyrite. Galena and its oxidation products occur in irregular lodes within the metamorphic area, principally at some distance from the porphyry masses. Gold ores with lead carbonate occur mainly as blanket lodes. Copper deposits replacing limestone have recently been discovered. These contain 10 per cent. copper.

Of many superficial showings of copper carbonates none have been developed profitably, but oxidized ores of relatively high grade have been discovered in the Alpha mine, at considerable depth. The principal deposits are the disseminated supergene

[1] LAWSON, A. C.: The Copper Deposits of the Robinson Mining District, Nevada. Cal. Univ., Dept. Geology *Bull.*, vol. 4, No. 14, pp. 287–357, 1906.
SPENCER, A. C.: The Geology and Ore Deposits of Ely, Nevada. U. S. Geol. Survey *Prof. Paper* 96, pp. 1–189, 1917.

ores in porphyry mined by the Nevada Consolidated Co. (Fig. 223). These deposits lie like a blanket with an average thickness of 218 feet and contain over 60,000,000 tons of ore carrying 1.7 per cent. of copper. They are capped by a mantle that has an average thickness of 103 feet, which carries only 0.05 per cent. of copper. Below the ore body the sericitized porphyry protore carries only 0.4 per cent. of copper.

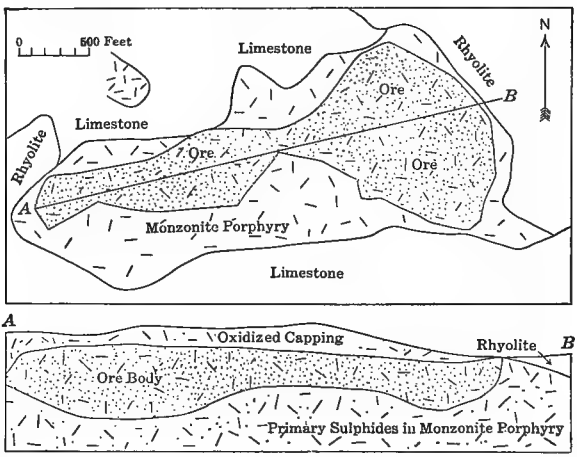


FIG. 223.—Map (above) and cross-section (below) of disseminated deposit in porphyry at Ely, Nev. (*Based on maps of Nevada Consolidated Copper Co.*)

Santa Rita, New Mexico.—The Santa Rita district,[1] in Grant County, New Mexico, is an area of limestone, sandstone, and shale of Paleozoic and Cretaceous age, intruded by dioritic and quartz monzonite porphyry. The deposits are disseminated in porphyry but differ from the disseminated deposits of Bingham and Ely, for much of the copper occurs as native metal and cuprite. Chalcocite evidently has replaced pyrite to form the rich secondary ore, but the chalcocite itself has been converted by oxidation processes to cuprite and native copper.

In the disseminated ores on the Chino ground 90,000,000 tons of ore averaging 1.75 per cent. of copper have been developed. Most of it is near the surface. The average thickness of the

[1] PAIGE, SIDNEY: The Geologic and Structural Relations of Santa Rita (Chino), N. Mex. *Econ. Geol.*, vol. 7, p. 547, 1913; U. S. Geol. Survey *Geol. Atlas*, Silver City Folio (No. 199), 1916.

LINDGREN, WALDEMAR, GRATON, L. C., and GORDON, C. H.: The Ore Deposits of New Mexico. U. S. Geol. Survey *Prof. Paper* 68, p. 305, 1910.

capping is 82 feet, and the average thickness of the ore below the capping is 107 feet.

Bisbee, Arizona.—The Bisbee (Warren) district,[1] in southern Arizona, is the leading copper-producing district in the State. Paleozoic quartzites and limestones resting on pre-Cambrian rocks were intruded by granite porphyry and after deep erosion were buried by Cretaceous sedimentary rocks, which have in greater part been eroded from the productive area.

The district is cut by numerous faults (Fig. 224). The primary ores were deposited during or after the intrusion of the granite porphyry and before the deposition of the Cretaceous beds. Deep oxidation and enrichment followed. The primary deposition was connected with contact metamorphism of the limestones, shown by the development of tremolite, diopside, garnet and other silicates, generally in crystals of microscopic

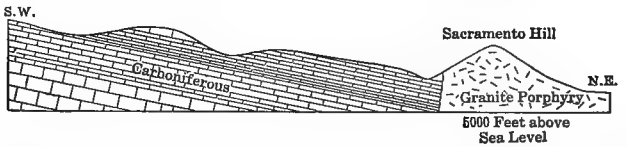


FIG. 224.—Section through part of Bisbee district, Arizona. Copper ores are developed replacing the limestone and disseminated in the granite porphyry. (*After Ransome, U. S. Geol. Survey.*)

size. The ore bodies first worked are those in the Carboniferous and Devonian limestones, but recent developments have discovered lenticular masses of ore in the Cambrian limestone, and disseminated chalcocite ore has been found in the porphyry. The ore in limestone is extensively enriched by chalcocitization. Much of it is deeply oxidized.

Morenci, Arizona.—The Morenci district,[2] in eastern Arizona, ranks high in the production of copper. It is an area of pre-

[1] RANSOME, F. L.: Geology and Ore Deposits of the Bisbee Quadrangle, Arizona. U. S. Geol. Survey *Prof. Paper* 21, 1904.

DOUGLAS, JAMES, NOTMAN, ARTHUR, LEGRAND, CHARLES, and LEE, G. B.: The Copper Queen Mines and Works. Inst. Min. and Met. *Trans.*, vol. 22, pp. 532–590, London, 1913.

RANSOME, F. L.: Notes on the Bisbee District, Arizona. U. S. Geol. Survey *Bull.* 529, pp. 179–182, 1913.

BONILLAS, Y. S., JENNEY, J. B., and FEUCHÈRE, LEON: Geology of the Warren District. Am. Inst. Min. Eng. *Trans.* vol. 55, pp. 284–352, 1916.

[2] LINDGREN, WALDEMAR: The Copper Deposits of the Clifton-Morenci District, Arizona. U. S. Geol. Survey *Prof. Paper* 43, 1905.

REBER, L. E.: The Mineralization at Clifton-Morenci. *Econ. Geol.*, vol. 11, pp. 528–573, 1916.

Cambrian granite and quartzitic schist, unconformably above which are Paleozoic sandstones, limestones, and shales that are locally overlain unconformably by Cretaceous shales and sandstones. These rocks are intruded by masses of granitic porphyries, which form stocks, dikes, laccoliths, and sheets. All these rock have been subjected to uplift, doming, and faulting. The domed area of older rocks is framed in by Tertiary lavas.

The ore bodies are veins and disseminated deposits in the granitic and quartz monzonite porphyry and contact-metamorphic deposits in the limestone and shale. The veins and disseminated deposits are most productive.

The ore deposits are in or near the intruding porphyry and were probably formed by solutions emanating from igneous bodies. The contact-metamorphic deposits have formed in Paleozoic limestone and shale near the porphyry. Pure limestones and calcareous shales were changed to ore consisting of pyrite, chalcopyrite, zinc blende, magnetite, garnet, epidote, diopside, tremolite, and quartz.

The veins cut granitic porphyry, and sedimentary rocks. They are composed of pyrite, chalcopyrite, sphalerite, molybdenite, sericite, and quartz.

The disseminated ores in porphyry are formed by filling small but closely spaced cracks in the porphyry and replacing the rock nearby. Some of these deposits are large, and they constitute the mainstay of the camp.

The veins and disseminated deposits owe much of their workable ore to processes of enrichment. Near the surface they are oxidized and generally leached of copper. Not all are marked by heavy gossans, and in the outcrops of some there is but little iron. Below the leached zone is a zone of chalcocite ore in which the copper sulphide replaces pyrite and zinc blende, below the chalcocite ore the primary sulphides are found including pyrite, chalcopyrite and sphalerite.

Ajo, Arizona.—The Ajo district,[1] in south-central Arizona, contains disseminated copper ores in porphyry, in which oxidation appears to have been attended by little leaching and chalcocitization. The most notable feature of this region is an intrusive mass of monzonite porphyry, which has domed up the older rhyolite beds (Fig. 225).

[1] JORALEMON, I. B.: The Ajo Copper-Mining District. Am. Inst. Min. Eng. *Trans.*, vol. 49, p. 593, 1915.

Some rich copper veins occur in the porphyry and in the rhyolite, but the most valuable deposits developed are in a mass of shattered porphyry that occupies about 55 acres and has a maximum depth of 600 feet, carrying about 12,000,000 tons of carbonate ore, below which lies about 28,000,000 tons of sulphide ore. Unlike the disseminated deposits at Bingham and Ely, in which the copper ore is largely chalcocite, the disseminated ores in the Ajo district are mainly chalcopyrite and bornite.

The outcrop and oxidized zone exhibit copper minerals conspicuously. They consist of silicified monzonite porphyry, with seams and stains of malachite, limonite, hematite, and a little chrysocolla. The oxidized ore extends downward to an almost horizontal plane about 150 feet below the highest hills. This plane is approximately the present ground-water level, and the transition from carbonate to sulphide ore is very abrupt.

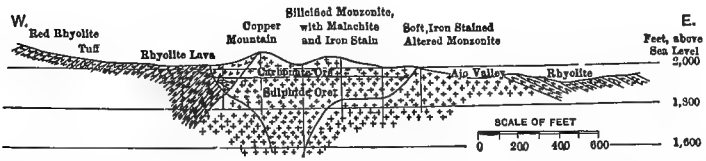


FIG. 225.—Vertical section through New Cornelia ore body, Ajo, Ariz. (*After Joralemon.*)

Globe, Miami, and Ray, Arizona.—Globe, Miami, and Ray are in Gila County, central western Arizona. Globe[1] is one of the oldest copper-bearing districts in Arizona, having produced almost steadily since 1881. It is in an area of pre-Cambrian crystalline rocks which include the Pinal schist and granitic intrusions. These are overlain by Paleozoic quartzites and limestones and intruded by diabase, granite, and quartz monzonite. The rocks mentioned are covered in places by dacite and by the Gila conglomerate.

The principal deposits of Globe are lodes and replacement deposits in limestone and diabase, of which the largest are in the Old Dominion mine. The primary ores consisted largely of pyrite and chalcopyrite, with bornite and specularite. These ores are oxidized to a depth of 800 feet and at places deeper and they contain copper as carbonates and cuprite. Enriched

[1] RANSOME, F. L.: Geology of the Globe Copper District, Arizona. U. S. Geol. Survey *Prof. Paper* 12, 1903.

chalcocite ore is found in and below the oxidized ore. Much of the ore contains about 6 per cent. of copper.

Miami[1] is about 6 miles west, and Ray about 20 miles southwest of Globe. They are the only districts known in the United States that contain large deposits of chalcocite ore disseminated in schist.

At Miami the Pinal schist is intruded by granite and granite porphyry. Disseminated deposits form a chain 2 miles long and a quarter of a mile in maximum width, from the Miami mine on the east through the Inspiration (Fig. 226), Keystone, and Live Oak mines toward the west. The surface is stained in places with iron oxide and copper carbonate. Leached material with little copper extends downward from 50 to 600

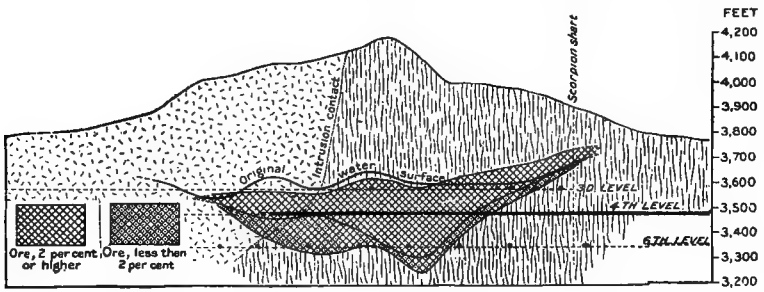


FIG. 226.—Section showing geology of Inspiration mine, near Miami, Ariz. (*After Ransome, U. S. Geol. Survey.*)

feet below the surface. Below that is a blanket of secondary chalcocite ore which has a maximum thickness of about 300 feet. Estimates give a total of 80,000,000 to 90,000,000 tons of ore averaging between 2 and 2.5 per cent. of copper. The ore of workable grade will probably amount to 150,000,000 tons. Although much of this ore lies so deep that it can not be mined profitably with steam shovels, it can be worked because it is of somewhat higher grade than the ore of porphyry mines that use steam shovels, and because the secondary ore carries very little pyrite. The mill concentrates are rich. They consist mainly of chalcocite, and only a small percentage of the ore milled is put through the smelter.

[1] RANSOME, F. E.: The Copper Deposits of Ray and Miami, Arizona. U. S. Geol. Survey *Prof. Paper* 115, pp. 1–192, 1919.

TOLMAN, C. F., JR.: Disseminated Chalcocite at Ray, Ariz. *Min. and Sci. Press*, vol. 99, pp. 622, 646, 1909.

The deposits at Ray[1] are similar to those of Miami. The Pinal schist is intruded by granite porphyry. The ore bodies are mainly in the schist, although masses of granite porphyry within the generally metallized area also have been converted to ore. The deposits are of the disseminated type; the siliceous, sericitized schist is sheeted, fractured, and filled with innumerable closely spaced veinlets of copper sulphides, which occur also in the schist between the veinlets. The protore is probably connected genetically with the granite porphyry. The ore bodies underlie a group of hills stained here and there with copper minerals. Within this area there is a continuous ore body about 8,000 feet long and 2,500 feet in greatest width. As at Miami, the layer of ore has many irregular undulations that apparently have no relation to the present topography. The average thickness of the ore body is 101 feet; of the overburden 250 feet. The depth to ore ranges from 10 to 300 feet, and the thickness of the ore from a thin film to 400 feet.

Jerome, Arizona.—The Jerome district[2] is in Yavapai County, east central Arizona. The largest mine of the district is the United Verde, which was once worked for gold but since 1888 has been a steady producer of copper, giving the district the sixth rank in the United States.

The United Verde mine is in an area of pre-Cambrain schists, faulted upward and overlain unconformably by Paleozoic beds. The ore shoot is oval in plan, about 1,300 feet long horizontally and 700 feet wide. It trends north-northwest and pitches in that direction 45°. It has been worked to a vertical depth of 1,200 feet. The great shoot is in reality a complex of smaller but nevertheless large irregular or lenticular ore bodies, showing a tendency toward parallelism with the schistosity.

The ore was deposited in pre-Cambrian time. The chief mineral is chalcopyrite, associated with which are pyrite specular-

[1] RANSOME, F. L.: Geology of the Globe District, Arizona. *Min. and Sci. Press.*, vol. 102, p. 747, 1911.

TOLMAN, C. F., JR.: Disseminated Chalcocite Deposits at Ray, Arizona. *Min. and Sci. Press*, vol. 99, p. 622, 1909.

RANSOME, F. L.: U. S. Geol. Survey *Bull.* 529, p. 186, 1913; *Bull.* 625, pp. 216–217, 1917.

[2] RANSOME, F. L.: U. S. Geol. Survey *Bull.* 529, p. 192, 1913; *Bull.* 625, pp. 232–233, 1917.

REBER, L. E.: Geology and Ore Deposits of Jerome District. Am. Inst. Min. Eng. "Mining and Metallurgy," No. 161, pp. 25–27, 1920.

ite and sphalerite. The sulphides occur partly in small irregular fractures and along planes of schistosity, but to a large extent they have replaced the schist.

Oxidized ore containing malachite, azurite, and cuprite extended to a depth of about 400 feet and in its upper part was comparatively rich in gold. Below the level of complete oxidation there was chalcocite ore with a relatively high proportion of silver. Recently large bodies of rich chalcocite ore inclosed in schist have been found in the United Verde Extension mine. These are capped by gossan, above which are flat-lying Cambrian sedimentary rocks. The chalcocite ore and the leached oxidized material above it have evidently resulted from weathering in pre-Cambrian time.

Shasta County, California.—The copper-bearing region of Shasta County, California,[1] is in the Klamath Mountains, a few miles north of Redding.

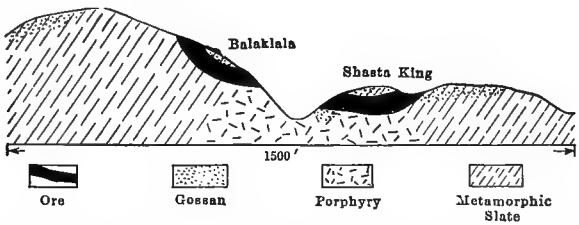


FIG. 227.—Cross-section of ore bodies at Balaklala, Shasta County, Cal. (*After Weed.*)

The valuable copper deposits consist of large masses of pyritic ore, in part replacing crushed and shattered zones of alaskite porphyry, which is highly altered by sericitization. The ore bodies are rudely tabular. The Bully Hill deposits, in the eastern district, are steeply pitching. The Shasta King and Balaklala, in the western district, are large flat-lying "lenses." Some of the deposits are over 1,200 feet long and 300 feet wide (Fig. 227).

The deposits are mineralogically simple. Pyrite is the most abundant mineral, and chalcopyrite is the chief copper mineral. The gangue minerals are gypsum, calcite, and barite. The

[1] GRATON, L. C.: The Occurrence of Copper in Shasta County, California. U. S. Geol. Survey *Bull.* 430, pp. 71–111, 1910.

BOYLE, A. C., JR.: The Geology and Ore Deposits of the Bully Hill Mining District, California. Am. Inst. Min. Eng. *Trans.*, vol. 48, pp. 67–115, 1915.

ores are believed to have been deposited by hot waters originating in alaskite porphyry. The minerals that have resulted from the alteration of the primary ore include limonite, wad, chalcopyrite, bornite, chalcocite, cuprite, native copper; malachite, azurite, and several sulphates. Some of the deposits contain considerable zinc blende.

Ducktown, Tennessee.—The mineral deposits of Ducktown are in the southeast corner of Tennessee, near the North Carolina line, and extend southward into Georgia. They were first worked in the late forties. Besides large amounts of copper they have produced 1,500,000 tons of iron ore and a relatively small amount of silver and gold. They yield at present, in addition

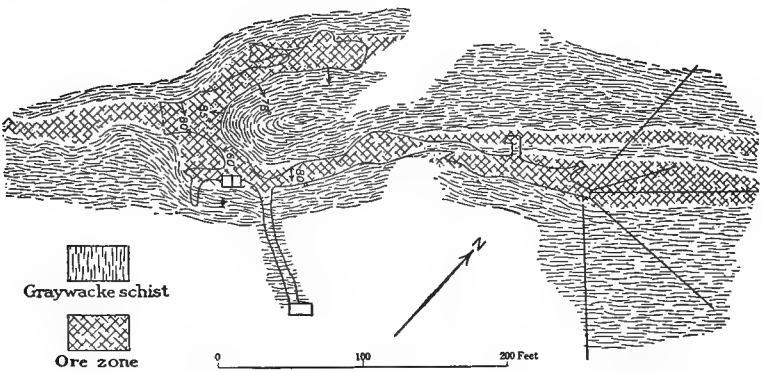


FIG. 228.—Plan of 20-fathom level, East Tennessee mine, Ducktown, Tenn.

to the metals, over 1,000 tons of sulphuric acid daily. The ore now worked carries less than 2 per cent. of copper. It is heavy iron sulphide ore, principally pyrrhotite, pyrite, and chalcopyrite.

The prevailing rocks of the district[1] are sandy schists and graywackes, with which are interbedded mica schists. The dominant series is the metamorphosed product of Cambrian sedimentary beds. The schists are cut by dikes of gabbro, which are not so highly metamorphosed by pressure as the sedimentary beds. The schistosity and the bedding of the sedimentary rocks strike nearly everywhere northeast, and the prevailing dip is southeast. These rocks have been folded into sharp folds, many of them isoclines. Many of the folds were broken along the

[1] EMMONS, W. H., and LANEY, F. B.: Preliminary Report on the Mineral Deposits of Ducktown, Tenn. U. S. Geol. Survey *Bull.* 470, pp. 151–172, 1911.

crests of anticlines and pass into strike faults that nearly everywhere dip southeast.

The ore bodies[1] (Fig. 228) are replacements of limestone lenses which without much doubt were originally deposited at a single stratigraphic horizon. Anticlines and faulted anticlines, which are characteristic of this region, are shown also in the ore zone. The ores themselves are somewhat metamorphosed by dynamic processes, and the gangue minerals are bent, but at most places they do not exhibit a well-defined schistosity.

The primary ore consists of pyrrhotite, pyrite, chalcopyrite, zinc blende, bornite, specularite, magnetite, actinolite, calcite, tremolite, quartz, pyroxene, garnet, zoisite, chlorite, micas, graphite, titanite and feldspars.

The deposits are not in contact with igneous rocks but are near intruding gabbro, and intruding granites are found a few miles away.

The gossan extends from the surface to a maximum depth of 100 feet. It carries 40 to 50 per cent. of iron, generally less than 12 per cent. of silica and alumina, and 0.3 to 0.7 per cent. of copper. The minerals are hydrous iron oxides, quartz, jasper, and kaolin, with a little cuprite, native copper, and sulphur. Below the gossan iron ores is a zone of rich copper ores, consisting of chalcocite and other copper minerals in a gangue of sulphates, quartz, and decomposed silicates. Under the higher portions of the outcrops of the lodes the top of this zone is about 100 feet below the surface, but the depth decreases down the slopes, and where the lodes are crossed by running streams the secondary copper ores are exposed at the surface. The zone is from 3 to 8 feet thick.

The secondary minerals include chalcanthite, chalcocite, chalcopyrite, cuprite, gypsum, and iron sulphate. Much of this secondary ore carries from 20 to 30 per cent. of copper.

Lake Superior Region.—The Lake Superior copper deposits[1] are in the Keweenawan, the upper series of the Algonkian. The Keweenawan series consists of interbedded basic lava flows,

[1] Irving, R. D.: The Copper-Bearing Rocks of Lake Superior. U. S. Geol. Survey *Mon.* 5, pl. 17, 1883.

Lane, A. C.: Geology of Keweenaw Point. Lake Superior Min. Inst., *Proc.*, vol. 12, p. 93, 1907.

Van Hise, C. R., and Leith, C. K.: The Geology of the Lake Superior Region. U. S. Geol. Survey *Mon.* 52, p. 575, 1911.

sandstones, and conglomerates, intruded by acidic and basic porphyries. A fault strikes northeastward along Keweenaw Point near its center. Southeast of the fault the copper-bearing

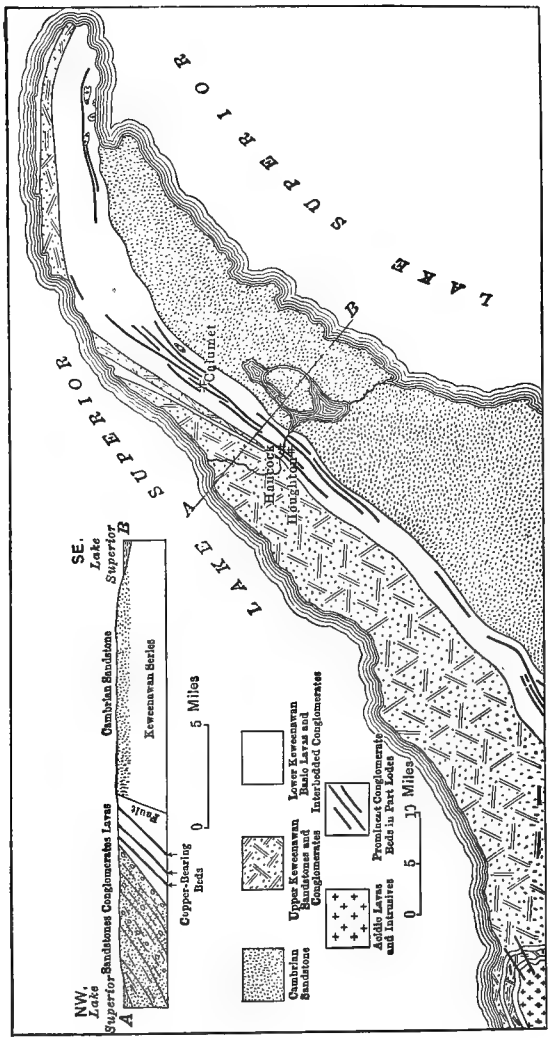


FIG. 229.—Sketch map and cross-section of the Keweenaw copper district, Michigan. (*Based on maps by Seaman and section by Lane.*)

beds are probably covered by the nearly horizontal Eastern (Cambrian) sandstone (see Fig. 229). Northwest of it the Keweenawan beds dip northwest at angles of 40° to 20° or less.

The copper deposits are in the main broad tabular bodies that strike and dip with the beds. The principal productive belt, which is in the Middle Keweenawan, extends from a point near Rockland, in Ontonagon County, northeastward to a point near Eagle River, a distance of about 70 miles. Numerous veins cut across the lodes. Nearly all the copper now mined occurs as native metal, although some copper as arsenides is obtained from veins that cross the lava beds in the Ahmeek mine. The copper content of the ore is low, ranging at present from about 0.6 to 2 per cent. A little native silver occurs with the copper; in the ore now mined it is almost negligible.

The principal gangue minerals are calcite, quartz, chlorite (delessite), prehnite, and laumontite, but considerable quantities of analcite, orthoclase, thomsonite, apophyllite, natrolite, and other zeolites are present, with many other minerals.

The copper of the bedded deposits replaces the conglomerates and amygdaloids, fills amygdules and other openings in them, and cements small fissures in the trap series. At present the amygdaloidal deposits supply about twice as much ore as the comglomerates. The latter are mined extensively in the vicinity of Calumet.

The amygdaloidal and conglomerate deposits extend great distances along the strike; the Kearsarge lode is mined almost without break for 14 miles, and other lodes are mined for 2 miles or more along their strike. They have been followed down the dip more than 1½ miles, or about 1 mile below the surface.

Copper is found at many stratigraphic horizons in the amygdaloids. Some of the lava flows are 100 feet thick or even thicker. At some places the amygdaloidal ore is at the top, at others at the bottom of the flow. In general the productive amygdaloids are mined for a width of 30 or 40 feet. At some places the amygdaloids carry copper for a width of only 3 or 4 feet; at such places they are generally unprofitable.

Although a number of conglomerate beds contain small amounts of copper, only two conglomerates, the Allouez and the Calumet, are workable. One of these, the Calumet, is the mainstay of the Calumet & Hecla Co., the greatest copper producer in the region. This conglomerate dips 39° NW. at the surface and is followed down the dip 8,100 feet, to a vertical depth of 4,748 feet.

The conglomerate lode is 13 feet wide at the surface and 20

feet wide in the deep workings. The upper half of the bed is richer than the lower half. The copper content of this conglomerate was about 4 per cent. near the surface, but a mile vertically below the surface it is only 1 to 1.5 per cent. The copper ores were probably deposited during the period of extrusion of the lavas and before the series was tilted. They are probably related genetically to intruding igneous rocks. Unlike native copper in other districts, the ore is believed to be primary.

Zeolitic copper ores are found associated with basic lavas in New Jersey[1] and at other places but none of them have yielded much copper.

Chitina Copper Belt, Alaska.—The Chitina copper belt, Alaska,[2] is an area of greenstone, mainly diabase, which is overlain by Triassic limestones. Above the limestones are later sedimentary rocks; all these rocks are cut by quartz diorite porphyry. The country is rugged, and the region of the deposits

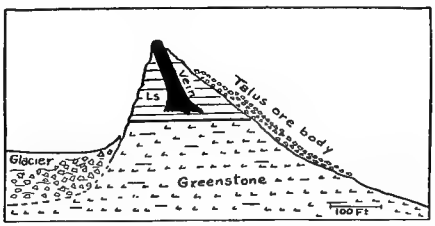


FIG. 230.—Diagrammatic cross-section of Bonanza mine, Chitina district, Alaska, showing glacier with ore and talus ore body on slope. (*After Bateman and McLaughlin.*)

has been deeply eroded. The principal deposits are rudely tabular masses of nearly pure chalcocite rich in silver, which occur in fractured or fissured zones in the limestone above the contact with greenstone.

The chalcocite ore extends to the very surface and accumulates in talus from the cliff (Fig. 230). Owing to the rapid mechanical disintegration and the cold climate little or no gossan is developed. Open cavities in the fractured limestone have been filled

[1] LEWIS, J. V.: The Newark (Triassic) Copper Ores of New Jersey. N. J. Geol. Survey *Ann. Rept.* for 1906, pp. 131–164, 1907.

LEWIS, J. V.: Notes on the paragenesis of the zeolites: Abstract, Science, new ser. vol. 35, p. 313, 1912; abstract (with discussion by A. C. Lane and F. R. Van Horn), Geol. Soc. America *Bull.*, vol. 23, p. 727, 1912.

[2] MOFFIT, F. H., and CAPPS, S. R.: Geology and Mineral Resources of the Nizina District, Alaska. U. S. Geol. Survey *Bull.* 448, 1911.

with ice, and both the country rock and the talus are frozen all summer except for a few feet at the surface. Tolman has shown that in the Bonanza mine chalcocite replaces bornite.

The principal deposits are those of the Bonanza and Jumbo mines, owned by the Kennecott Copper Co. As stated by Bateman and McLaughlin,[1] the veins in a general way may be considered as extremely thin wedges which gradually taper upward toward their apex and whose bases rest on an inclined fault or bedding plane. The length of the inclined wedges along their base is many times greater than their height from base to top. The height of most of the veins has been determined, but lengthwise along their base they are still being followed by inclined shafts (Fig. 231). The average height of the main Bonanza vein from base to top, measured normal to the incline, is about

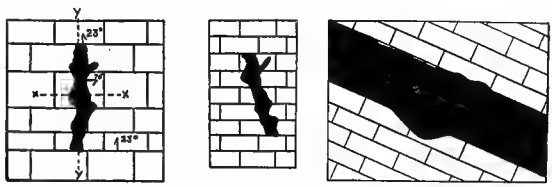


FIG. 231.—Diagrams showing shape of irregular replacement ore body in the Chitina district, Alaska, and its relation to bedding planes. (*After Bateman and McLaughlin.*)

210 feet in the upper levels and 150 feet on the lower levels. The vein has been followed for a distance of about 1,900 feet, measured along its base, and the width varies from 2 to 50 feet. The chalcocite is oxidized and changed to carbonates near the surface, but no gossan is developed. It crops out on the surface and has accumulated as talus and in a glacier below the outcrop. The deposits are remarkable for the richness and unique character of the ore. There is no evidence of primary ore adequate to supply the material from which the chalcocite might have been derived. Some investigators have regarded the ore of primary, others of secondary origin. Bateman and McLaughlin are inclined to the hypothesis that the ore is of deep-seated origin. This hypothesis appears probable for many reasons. One of the most convincing is that some of the deposits are blind or terminate upward against barren rock.

[1] BATEMAN, A. M., and MCLAUGHLIN, D. H.: Geology and Ore Deposits of Kennecott, Alaska. *Econ. Geol.*, vol. 15, p. 30, 1920.

CHAPTER XIX

GOLD AND SILVER

GOLD

Minerals	Percentage of gold	Composition
Native gold	100.0	Au
Gold amalgam	.....	Au,Hg
Electrum	.....	Au,Ag
Calaverite	39.5	$(Au,Ag)Te_2$
Krennerite	39.5	$(Au,Ag)Te_2$
Sylvanite	24.5	$AuAgTe_4$
Petzite	25.4	$(Au,Ag)_2Te$

Except placers, nearly all workable deposits of gold are veins and related deposits formed by ascending hot waters. In veins gold is deposited at all depths. On weathering gold is concentrated mechanically in placers, and the outcrops of its deposits are enriched by the removal of other materials more rapidly than gold.

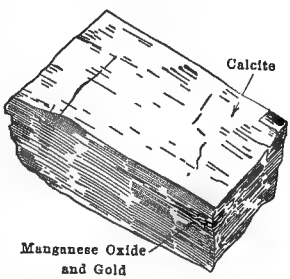


FIG. 232. — Calcite crystal that was immersed in a manganiferous acid gold solution. Gold and manganese dioxide have been precipitated together in cleavage cracks.

Unlike copper and silver, gold is not dissolved by sulphuric acid or ferric sulphate. It is not dissolved by sulphuric acid even if chlorides are present, but if acid, chloride, and manganese oxide are present "nascent chlorine" is formed, and in this state chlorine dissolves gold in an acid solution. If the solution becomes alkaline the gold will be precipitated. Very frequently gold is precipitated together with manganese oxide. Calcite or any other mineral that neutralizes acid will cause gold to be precipitated from the chloride solution (Fig. 232). Much of the rich secondary or supergene gold ore consists of calcite and other gangue minerals

plastered with gold and manganese oxide or containing them in cracks and fissures. As a rule manganiferous deposits do not yield rich placers, although in some of them secondary gold ores have been concentrated at or very near the surface. The production of gold in the United States in 1920 amounted to $49,509,400.

GOLD PLACERS

General Features.—A large part of the world's gold has come from placers. Placer deposits as a rule are the most easily discovered of all metalliferous deposits, and because their product is so easily transported and marketed the placers are commonly the first resources of a region to be exploited. The lure of gold has resulted in the exploration and development of many a new country.

As a land surface is worn away in regions where conditions are unfavorable for solution, gold contained in veins and veinlets or disseminated in the rock tends gradually to become concentrated at the surface. Some of it may remain practically in place. The rotten outcrops (saprolites) of many veins in the southern Appalachians were washed for gold.[1] As erosion goes on the gold-bearing mantle rock of a deposit on a slope will gradually settle downhill, constituting an eluvial deposit. As erosion is continued further, however, the gold ultimately finds lodgment in streams together with sand and gravel. Such accumulations constitute the principal placer deposits.

In placer mining commonly a box-like trough, called a sluice, is fitted on the bottom with movable cross pieces or riffles. Although tons of rock may be washed through the sluice, nearly all the gold collects in the pockets behind the riffles. The bed of a stream acts much like the placer miner's sluice. The gold sinks to the bottom and remains on bedrock, especially in joints and seams or in low places in the bed. As gold (specific gravity 15.6 to 19.3) is about six to seven times as heavy as rock (specific gravity 2.5 to 3), it will sink, except the very fine dust, which may be carried away. The coarser gold generally remains in gulches and creeks near its source, forming gulch and creek gravels; the finer gold may be carried to rivers and supply gold for river gravels; some gold may be carried even to the sea.

[1] Becker, G. F.: Gold Fields of the Southern Appalachians. U. S. Geol. Survey *Sixteenth Ann. Rept.*, part 3, p. 289, 1895.

Where a shore line is receding by wave action the gold may be concentrated along the beaches as beach placers or marine placers. At Nome, Alaska,[1] placer deposits occur both along streams and along the beach.

Placers formed in gulches, in beds of rivers, or on the sea shore may be elevated by general uplift of the region to levels above the present drainage lines or along the coast far above sea level. As streams approach grade they meander in their flood plains, and gold contained in flood-plain deposits may be distributed over wide areas. In the normal history of erosion a stream will cut below its flood plain, and the abandoned flood plain will later appear high above the stream as a terrace. Some deposits worked for placer gold are far above the present streams (Fig. 233).

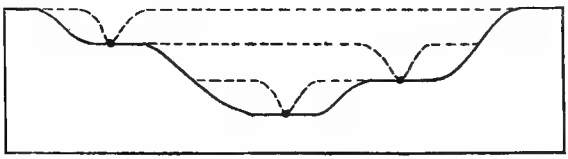


FIG. 233.—Sketch showing placer deposits on terraces of a stream. These were formed when the terraces were parts of the flood plain of the stream. (*After Tyrrell.*)

Placer deposits may be buried under later deposits. Lava flows that are extravasated upon a rugged surface containing placers generally cover the lower areas—the bottoms of valleys. The streams that subsequently flow over the lavas will take new courses, and after they have sunk their beds below the ancient beds that were filled by the lavas the gold deposits will crop out on hillsides where the ancient channels are crossed by the later ones. Such ancient gravels in California have yielded much gold. As the land surface is eroded the gold in the old channels is carried down into present stream valleys. Thus the gold-bearing gravels in present channels may represent not only the waste of lodes that are now being eroded, but reconcentrations from ancient placers that were recently exhumed.

Scour and Fill.—There is a strong tendency for gold to work downward in gravels. It may halt at a stiff clay seam in the

[1] COLLIER, A. J., HESS, F. L., SMITH, P. S. and BROOKS, A. H.: The Gold Placers of Parts of Seward Peninsula, Alaska. U. S. Geol. Survey *Bull.* 328, 1908.

gravel bed, or it may descend to the bedrock and be concentrated in joints and fractures of the rock. Cross-currents, eddies, and whirlpools are common features of streams, and normal stream erosion is attended by extensive reassortment of stream deposits.

The development of potholes is common in swift streams, and even sluggish streams scour the loose unconsolidated materials of their beds. Soundings in rivers show that deep holes are sunk in fluvial deposits by running water. Even the more sluggish streams that are filling their channels will continually reassort the material deposited in them by dropping the coarse and picking up the fine. In flood time material is deposited on the flood plain, but at the same time material in the main or central channel may be picked up and carried downstream because the velocity and volume of the stream are greater than during low water. At Nebraska City, Nebr.,[1] the scouring action is known to extend to depths of 70 to 90 feet. Holes scoured out at one time will be filled later. Thus material is continually agitated and shifted downstream, and any gold present tends to settle to bedrock. In gold-bearing gravels the gold is generally greatly concentrated on bedrock. Dredging or sluicing operations yield the greatest profit, as a rule, from the material lying within a few inches of the bottom of the gravel bed.

Where the grade of a swift stream becomes lower gravels with contained gold will accumulate. Alluvial fans, gravel plains, or any other depositional features may be the sites of placer gold.

Relation of Gold Placers to Gold Lodes.—Where gold lodes are exposed it is reasonable to expect placers, and where placers have been found the search for the source of their gold suggests interesting possibilities for prospecting. An experienced prospector will pan the gravels of gulches that drain a region which contains gold deposits and will seek gold lodes in a region which contains gold-bearing gravels.

Not all gold-lode deposits, however, have associated placers. In some regions gold is dissolved and carried downward in solution, enriching the deposit below. Even where gold is not dissolved it is not invariably concentrated in gravels. It may be so finely divided that it is carried away in the drainage.

Conversely, in some regions that contain placer deposits no workable gold lodes have been discovered. Where gold is not

[1] CHAMBERLIN, T. C. and SALISBURY, R. D.: "College Geology," pp. 184–185, 1909.

dissolved from its deposits, weathering and erosion are generally very efficient processes in the mechanical concentration of gold. Hundreds or even thousands of feet of material may be eroded from a region, the rock being carried away in streams, whereas the heavier gold remains behind to enrich gravels near the deposits. In some regions the gold in gravels has been concentrated from many veins and veinlets that are too small and too low in grade to be worked underground. Many quests for the "mother lodes" in regions containing valuable placers have proved disappointing.

Eolian and Glacial Deposits Containing Gold.—Where rocks are deeply decayed in arid countries where strong winds blow, the lighter particles may be blown away from outcrops of deposits, leaving the heavy material in a more concentrated state. The deposit becomes enriched in the coarse gold that is left behind. Placers have formed in western Australia by such processes.[1]

When glaciers erode a gold-bearing area the mantle rock, gravel and loose material at outcrops of lodes will be carried away in the ice and any gold it contains will become incorporated in the drift. There is very little sorting, however, and comparatively few glacial deposits are valuable except where the material has been worked over by running water.

Buried Placers.—Not only are placer deposits being formed today, but they have been formed where conditions were favorable during and since pre-Cambrian time. In the Black Hills, (Fig. 234), the Cambrian basal conglomerate and sandstone rest unconformably above the pre-Cambrian schist series that contain the Homestake lode, and in the conglomerate are found rounded grains of gold, evidently derived from the pre-Cambrian deposits. Associated beds contain Cambrian marine fossils. The deposits are believed to have been formed along an ancient shore.[2]

[1] HOOVER, H. C.: The Superficial Alteration of Western Australian Ore Deposits. Am. Inst. Min. Eng. *Trans.*, vol. 28, pp. 762–763, 1899.

RICKARD, T. A.: The Alluvial Deposits of Western Australia. Am. Inst. Min. Eng. *Trans.*, vol. 28, pp. 490–537, 1899.

[2] DEVEREUX, W. B.: The Occurrence of Gold in the Potsdam Formation, Black Hills, Dakota. Am. Inst. Min. Eng. *Trans.*, vol 10, pp. 465–475, 1882.

IRVING, J. D.: Economic Resources of the Northern Black Hills. U. S. Geol. Survey *Prof. Paper* 26, pp. 98–111, 1904.

Where land sediments or lavas cover stream beds, the stream placers will be preserved. The most productive buried placers of North America are the Tertiary gravels of California, which, according to Lindgren[1] have yielded about $300,000,000. This region in early Tertiary time was less rugged than it is today (Fig. 235), and on its gentle surface gold accumulated in streams

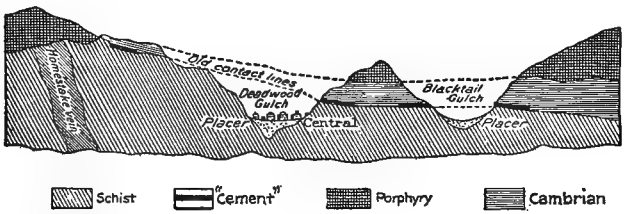


FIG. 234.—Geologic section of Homestake vein, Black Hills, South Dakota. The "cement" mines are Cambrian placers. (*After Devereux.*)

from the weathered lodes near by. The gravel beds were covered with rhyolite tuffs, andesitic breccia, and basalt, in places as much as 1,500 feet deep. Later the country was elevated, and deep canyons were sunk in its surface. The new drainage lines did not follow the former ones, and the ancient gravel beds where crossed by later canyons are now exposed, some of them hundreds

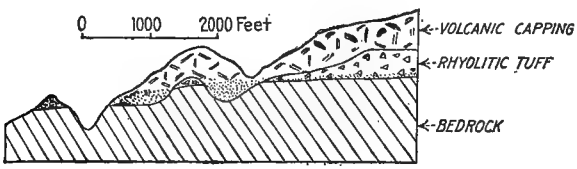


FIG. 235.—Section of Swift Shore mine, Placer County, California, showing gold-bearing Tertiary deposits (dotted portions) buried below lava capping. (*After Browne.*)

of feet above present streams. As the canyons are widened, gold in the ancient gravels is reconcentrated in the present gulches, where it mingles with material that is accumulated from the weathered outcrops of the lodes.

[1] LINDGREN, WALDEMAR: The Tertiary Gravels of the Sierra Nevada of California. U. S. Geol. Survey *Prof. Paper* 73, p. 81, 1911—Mineral Deposits, p. 206, New York, 1913.

Witwatersrand Auriferous Conglomerates.—The auriferous conglomerates of Witwatersrand, Transvaal, South Africa,[1] which are the most productive gold deposits of the world, yield about $180,000,000 annually. The country is a hilly area of crystalline schists and intruding granites upon which rest unconformably slates, quartzites, and conglomerates belonging to the Witwatersrand system, which is probably pre-Cambrian (Fig. 236). Above the Witwatersrand strata are conglomerates, lavas, and breccias of the Ventersdorp system; above the Ventersdorp unconformably is the Potchefstroom system, which is overlain (also unconformably) by the Table Mountain sandstones, of Devonian age. Higher still in the series are the coal-

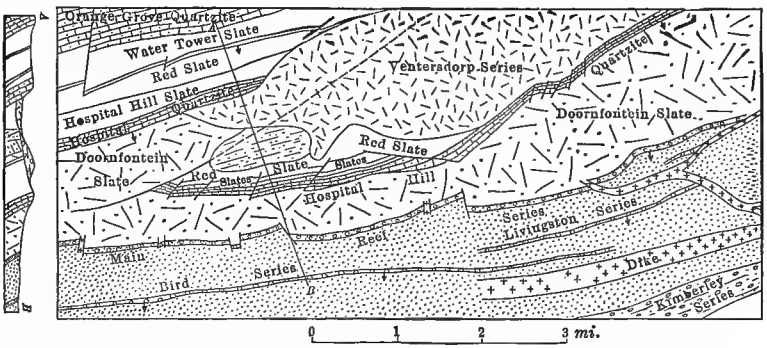


FIG. 236.—Plan and cross-section of part of Witwatersrand region, South Africa. (*Based on map by Hatch.*)

bearing Karoo beds, which are probably of Carboniferous age. The Witwatersrand beds are faulted and crossed by diabase dikes.

The principal gold deposits are in the upper Witwatersrand series, which is predominantly quartzite but contains four conglomerate zones, which carry gold. These are the Kimberley series, Bird Reef series, Livingstone Reef series, and Main Reef series. The Main Reef series has been worked more or less continuously for a distance of 46 miles.

In the Central Rand (the district near Johannesburg) the bulk of the gold is obtained from the Main Reef and from the South Reef. The conglomerates of the Main Reef consist mainly of rolled fragments of quartz pebbles, with fragments of quartzite,

[1] HATCH, F. A., and CORSTORPHINE, G. S.: Petrography of the Witwatersrand Conglomerate. S. A. Geol. Soc. *Trans.*, vol. 7, part 2, pp. 97–109, 1904.

HATCH, F. A.: The Conglomerate of the Witwatersrand, in BAIN, H. F., and others: "Types of Ore Deposits," pp. 202–218, San Francisco, 1911.

banded chert, and slate. The pebbles, which are worn smooth and round, lie in a matrix which originally consisted of quartz sand but which by the deposition of silica has been converted into a compact mass of quartz. Other constituents of the matrix that are undoubtedly original are zircon and chromite.

The minerals later than the quartz pebbles include chloritoid, sericite, calcite, tourmaline, rutile, pyrite, marcasite, pyrrhotite, chalcopyrite, zinc blende, galena, stibnite, cobalt and nickel arsenides, graphite, and gold telluride.

The origin of the gold in the Rand conglomerates is still in doubt. Gregory,[1] Becker,[2] and others have maintained that it is of placer origin, formed by concentration from the Swaziland schists, which carry stringers of quartz and gold. They state that the gold is concentrated in the lower parts of the beds and attribute its angular or crystalline condition to recrystallization, which would obliterate rounded surfaces of the minute particles of gold that predominate in the conglomerates. Facts that are urged as opposed to the theory that the gold was carried into the conglomerates by hot solutions are: an absence of hydrothermal metamorphism, a fairly regular distribution of gold in the conglomerate and an absence of gold in wall rock along fractures and cross-channels.

Some of the closest students of the area, however, believe that the gold was brought into the conglomerate in solution, together with other metallic minerals, among them pyrite, sphalerite, galena, and many other sulphides. Some see a generic relation between the gold deposits and dikes that cut the ore-bearing beds. A third hypothesis, not improbable, is that there has been some infiltration of mineral-bearing thermal waters since the gold was deposited as placers.

GOLD LODES

Porcupine, Ontario.—The Porcupine gold district,[3] is in northern Ontario, about 100 miles northwest of Cobalt. Pre-Cambrian

[1] Gregory, J. W.: The Origin of the Gold in the Rand Goldfield. *Econ. Geol.*, vol. 4, pp. 118–129, 1909.

[2] Becker, G. F.: The Witwatersrand Banket, with Notes on other Gold-Bearing Pudding Stones. U. S. Geol. Survey *Eighteenth Ann. Rept.*, part 5, p. 169, 1897.

[3] Burrows, A. G.: The Porcupine Gold Area. Ontario Bureau of Mines *Twenty-fourth Ann. Rept.*, part 3, 1915.

Hore, R. E.: The Nature of Some Porcupine Gold Quartz Deposits. Canadian Min. Inst. *Jour.*, vol. 14, p. 171, 1911.

rocks are intruded by granite and by diabase dikes. The prevailing rock is a green igneous rock (mainly basalt) which is cut by dikes of quartz porphyry. Above the Keewatin are Huronian quartzite and slate, altogether at least 400 feet thick. This series is tilted and locally rendered schistose. Granite (Laurentian) is intruded in the Keewatin and possibly in the Huronian also.

The ore deposits are veins and great irregular masses of schist seamed and impregnated with quartz and gold. Some of the deposits crop out conspicuously, among them the Dome and West Dome, so called from the shape of the outcrops at the places of discovery. The domes on the Dome property were about 100 by 125 feet. The deposits occur in both the Keewatin and Huronian rocks, and generally the lodes cut across the schistosity. The lodes range in attitude from horizontal to vertical and show a strong tendency to parallelism. The Hollinger group strikes northeast; the Dome group nearly east. Spectacular showings occur on many properties, although much of the ore is of low grade.

Besides quartz and pyrite the veins carry feldspar, tourmaline and carbonates, copper pyrite, galena, zinc blende, and pyrrhotite. These veins were probably formed at great depths and under high pressures, as is suggested by the presence of tourmaline and gas inclusions in the quartz. Burrows believes that they are closely related to granitic intrusions.

Southern Appalachian Region.—A belt of ancient rocks, consisting of crystalline schists and granites and other igneous rocks, extends from Alabama northeastward to Maine. In this belt several small deposits of gold have been found in Maine, New Hampshire, and several other States, but none north of Virginia has produced much gold. Valuable deposits[1] are located in Alabama, Georgia, and the Carolinas. Gold has been mined in

[1] BECKER, G. F.: Gold Fields of the Southern Appalachians. U. S. Geol. Survey *Sixteenth Ann. Rept.*, part 3, pp. 250–331, 1895.

GRATON, L. C., and LINDGREN, WALDEMAR: Reconnaissance of Some Gold and Tin Deposits of the Southern Appalachians. U. S. Geol. Survey *Bull.* 293, 1906.

MCCASKEY, H. D.: Notes on Some Gold Deposits of Alabama. U. S. Geol. Survey *Bull.* 340, p. 36, 1908; U. S. Geol. Survey *Mineral Resources*, 1908, part 1, pp. 645–681, 1909.

TABER, STEPHEN: Geology of the Gold Belt in the James River Basin, Virginia. Va. Geol. Survey *Bull.* 7, pp. 1–271, 1913.

the southern Appalachians since early in the nineteenth century. The total production is over $50,000,000.

The Appalachian gold veins are almost uniformly of low grade. They were formed in the deep zone. Some of them are closely associated with granitic intrusions. The minerals include quartz, sericite, biotite, fluorite, gold, pyrite, galena, zinc blende, pyrrhotite, chalcopyrite, and magnetite.

Few of these deposits have been extensively explored in depth. Many of them are profitable near the surface, partly by reason of the rotten condition of the rock, which renders it more easily worked, and partly because gold is enriched by the removal of valueless material. At the Haile mine, near Kershaw, S. C., the deposits are in quartz-sericite schist and metamorphosed igneous rocks. Large diabase dikes cut the schist, and near them the ore bodies are developed.

Black Hills, South Dakota.—The Black Hills of South Dakota,[1] which yield annually about $7,500,000 in gold, silver, and lead, constitute a domical uplift, rising above the Great Plains. The central peaks are of pre-Cambrian schists. They slope gradually outward to a rim of Paleozoic rocks that dip away from the hills. The sedimentary rocks (Fig. 237), including those as late as Cretaceous, are cut by many varieties of igneous dikes, stocks, and laccoliths. Alkali-rich rocks such as syenite porphyry and phonolite are represented. As the Tertiary (Oligocene?) beds at Lead contain pebbles of the porphyries the latter are presumably early Tertiary.

The deposits are (1) gold deposits in pre-Cambrian schists; (2) ancient placers in the Cambrian basal conglomerate; (3) siliceous gold ores replacing thin calcareous beds in the Cambrian; (4) gold-bearing replacement veins in Carboniferous rocks; (5) silver-lead replacement veins in Cambrian and Carboniferous rocks; and (6) recent placers.

The pre-Cambrian ores of the Homestake group (Fig. 238) are

[1] Irving, J. D., Emmons, S. F., and Jaggar, T. A.: Economic Resources of the Northern Black Hills. U. S. Geol. Survey *Prof. Paper* 26, 1904.

Sharwood, W. J.: Analyses of Some Rocks and Minerals from the Homestake Mine, Lead, S. D. *Econ. Geol.*, vol. 6, p. 729, 1911.

Devereux, W. B.: The Occurrence of Gold in the Potsdam Formation, Black Hills, Dakota. Am. Inst. Min. Eng. *Trans.*, vol. 10, p. 465, 1882.

Paige, Sidney: Pre-Cambrian Structure of the Northern Black Hills, South Dakota, and Its Bearing on the Origin of the Homestake Ore Body. Geol. Soc. America *Bull.*, vol. 24, pp. 293–300, 1913.

in a belt 3 miles long and 2,000 feet wide. The rocks are quartzites and mica schists (metamorphosed sediments) and amphibolites. Pre-Cambrian granite crops out not far away. The principal deposits replace a closely folded metamorphosed calcareous bed. The minerals of the ore are quartz, dolomite, calcite, pyrite, arsenopyrite, pyrrhotite, and gold, with which are associated the minerals of the schist—quartz, orthoclase,

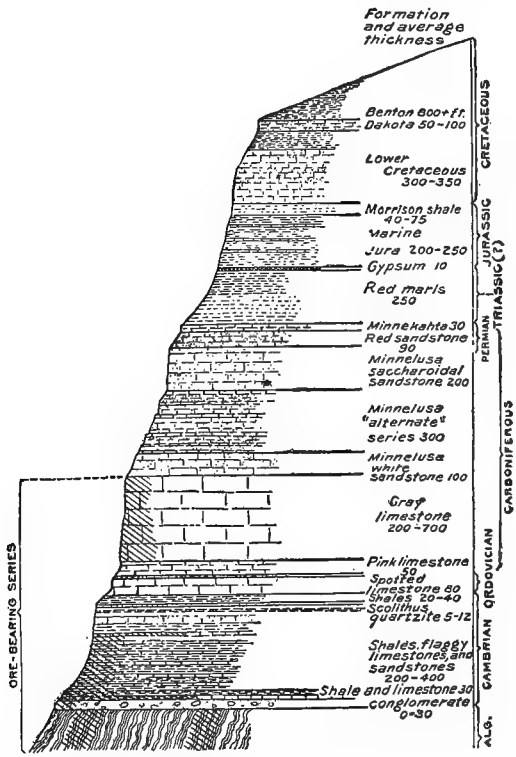


Fig. 237.—Generalized columnar section of northern Black Hills, South Dakota. Cross lining indicates metallized horizons. (*After Jagger, U. S. Geol. Survey.*)

hornblende, biotite, garnet, tremolite, actinolite, titanite, and graphite. The ore bodies are cut by many dikes of porphyry but apparently have not been much affected by them. The ores are of low grade.

The valuable minerals extend downward as far as exploration has gone and are fairly uniform to depths 2,000 feet or more below the surface. In general enrichment by surface leaching is subordinate.

Near the Homestake mine are flat-lying conglomerates at the base of the Cambrian that contain considerable detrital gold, evidently derived from the Homestake deposits. The general relations are shown by Fig. 234.

Valuable ore bodies were formed also in the Tertiary period. The chief of these are long, flat-lying ribbons of ore in the Cambrian, not far above its base. Some of these deposits are nearly 1 mile long; they are from 10 to 300 feet wide and have an average thickness of about 6 feet. The minerals are pyrite, quartz, fluorite, gold, and some silver. They are found where the limestone beds are crossed by small fractures called verticals.

Gold-silver replacement veins in Carboniferous rocks are found near Ragged Top, a laccolithic body of phonolite. The lodes are silicified brecciated zones in limestone. The minerals are pyrite, opaline silica, fluorite, and tellurides (probably sylvanite).

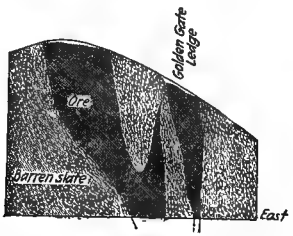


Fig. 238.—Section of Homestake ore body, Black Hills, South Dakota. (*After Irving, U. S. Geol. Survey.*)

Silver-lead deposits in the Cambrian and Carboniferous rocks were formerly productive. Some are replacement deposits along fractures in sedimentary rocks and porphyries. Tungsten deposits are extensively mined in the Cambrian sedimentary beds. These are mentioned on page 438.

California Gold Belt.—The California gold belt extends northwestward, with some interruptions, through the length of the State and continues northward into Oregon but disappears beneath Tertiary lavas, to reappear in British Columbia and Alaska. The lodes, with associated gold deposits of the same general type and placers derived from them, have produced over $1,350,000,000 in gold.

The lowest series in the geologic column is a greatly folded and metamorphosed complex consisting of Paleozoic sedimentary rocks and interbedded lavas, called the Calaveras formation.

Above this complex are Jurassic and Triassic rocks, less intensely folded than the Calaveras. Intruded into these is an enormous granodiorite batholith which forms the main mass of the range. On and near the boundary of the central intrusive mass are many smaller bodies of granodiorite, diorite, and gabbro. These are doubtless of about the same age and of similar origin. As the Mariposa formation (Jurassic) is intruded by the granodiorite, and as the Chico (Cretaceous) is not intruded by it, the age of the batholith is known to be early Cretaceous.

The gold deposits[1] are notably sparse in the central granodiorite belt but are clustered in and around the smaller intruding bodies, especially on the west slopes of the Sierra. The deposits are veins. Some of them are arranged in conjugated systems—for example, those at Nevada City, Grass Valley, and Ophir.

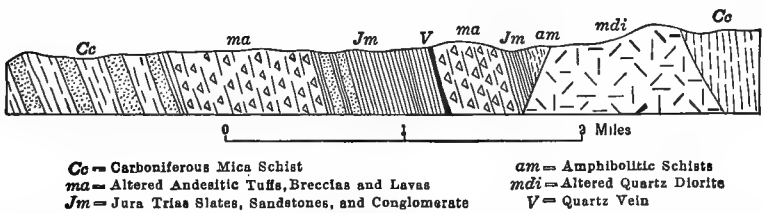


FIG. 239.—Cross-section of Mother Lode region, California. (*After Ransome, U. S. Geol. Survey.*)

The Mother Lode (Fig. 239) is a belt of strong, closely spaced veins over 100 miles long and not much more than a mile wide. It parallels the axis of the range and the general trend of the formations. Many veins of this group strike about N. 25° W. and dip about 60° E. Single deposits are developed for more than a mile along the strike.

As a rule the deposits are of low grade, the average tenor being about $4 a ton. Some mines exploit large bodies of ore that carry less than $3 a ton, but pockets of very rich ore have been found. The principal gangue minerals are quartz, carbonates, and albite. As a rule the gold is associated with sulphides including pyrite, arsenopyrite, and pyrrhotite, with pyrite,

[1] LINDGREN, WALDEMAR: Gold-Silver Veins of Ophir, Calif. U. S. Geol. Survey *Fourteenth Ann. Rept.*, part 2, pp. 243–284, 1894. The Gold-Quartz Veins of Nevada City and Grass Valley, Calif. U. S. Geol. Survey *Seventeenth Ann. Rept.* part 2, pp. 1–262, 1896.

RANSOME, F. L.: U. S. Geol. Survey *Geol. Atlas*, Mother Lode district, folio (No. 63), 1900.

chalcopyrite, and galena. Specularite, magnetite, tetrahedrite, molybdenite, telluride, and scheelite occur only locally. The sulphides constitute only a small percentage of the ore. By mechanical concentration deposits of very low grade are profitably worked.

There is no evidence that these deposits have been enriched by redeposition of gold; the outcrops are as rich as or richer than the ores in depth, and some of the deposits have been followed down the dip nearly a mile without notable change in value. Placers of enormous extent and value occur in this belt and have yielded more than half the gold derived from the deposits. At some places extensive stream placers are covered by Tertiary lavas. Doubtless many thousand feet of material has been eroded from these veins to supply the placer gold. They are nevertheless classed with veins formed at intermediate depths, for minerals indicating high temperature and pressure are only

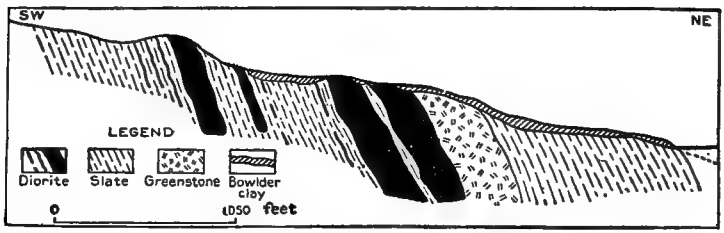


FIG. 240.—Cross-section through Alaska Treadwell mine and north side of Douglas Island, Alaska. (*After Spencer, U. S. Geol. Survey.*)

sparingly and locally developed. As a whole the group forms a transition type between the ores formed in the deep-vein zone and those formed at moderate depths.

Juneau, Alaska.—The California gold belt extends northward into Oregon and Washington, and in much of the area of these States it is probably below later lavas. Farther north rocks and deposits nearly related to those of the California gold belt are present in abundance. The Treadwell group of mines, on Douglas Island, exploited the most productive lode deposits in Alaska. The principal workings were flooded by sea water in 1917. On the mainland, across the narrow Gastineau Channel, a short distance from the Treadwell mines, the Alaska Gold Mines Co. and the Alaska Juneau Co. have developed great auriferous deposits of very low grade.

The rocks of this region consist of Paleozoic greenstones

slates, and schists intruded by gabbro, diorite, and diorite, porphyry.

At the Treadwell[1] mines (Fig. 240) great dikes of diorite intrude

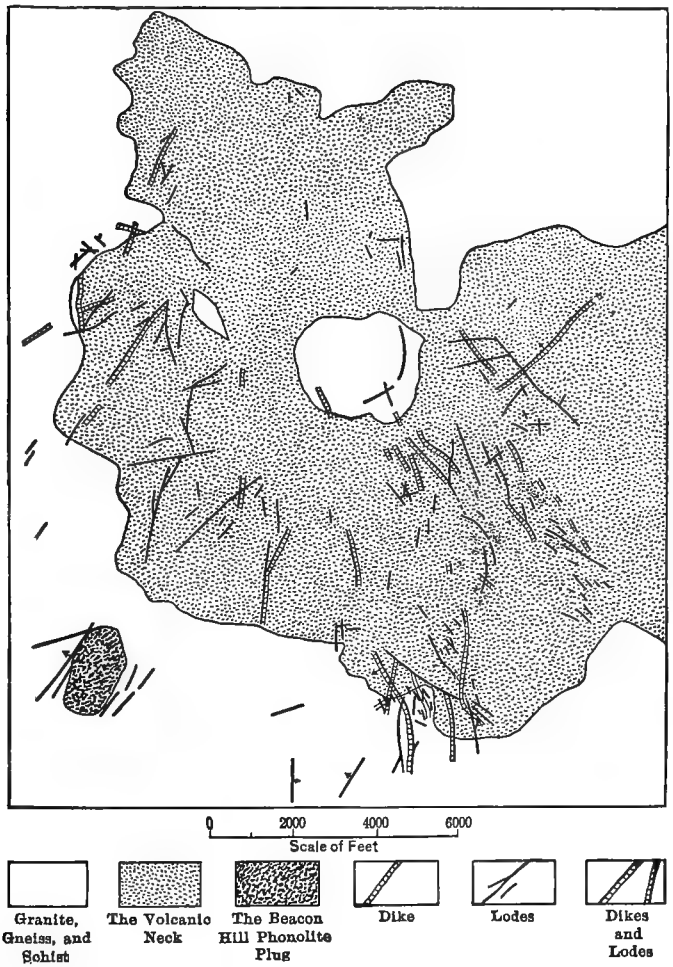


FIG. 241.—Plan showing the principal fissures of the Cripple Creek district, Colorado, on plane 9,500 feet above the sea. (*Based on map by Lindgren and Ransome, U. S. Geol. Survey.*)

the greenstones and schist, and the shattered diorite has been

[1] SPENCER, A. C.: The Juneau Gold Belt, Alaska. U. S. Geol. Survey *Bull.* 287, 1906.

HERSHEY, O. H.: Geology of the Treadwell Mines. *Min. and Sci. Press,* vol. 102, pp. 296–300, 334–335, 1911.

extensively replaced by mineralizing solutions and cemented by low-grade gold ore.

Cripple Creek, Colorado.—The Cripple Creek district, Colorado;[1] in the high country southwest of Pikes Peak, has produced over $250,000,000 in gold.

The oldest rocks of the region are pre-Cambrian granite, gneiss, and schist. A volcanic neck of Tertiary age 2 or 3 miles in diameter breaks through the pre-Cambrian rocks (page 447). This neck is the core of a volcano through which lavas were thrown out upon the ancient rocks, but most of the lavas have been removed by erosion. The volcanic neck is composed mainly of tuffs and breccias which are cut by dikes and stocks of latite-phonolite, and other alkali-rich intrusives. Phonolite and basic dikes cut the Tertiary rocks and the pre-Cambrian rocks near the volcanic center. The ore deposits are veins that were formed soon after the basic dikes. Many of them lie along the walls of the dikes and, like the dikes, are rudely radial about the volcanic neck (Fig. 241). The veins were formed by filling small openings along fissures and sheeted zones and subordinately by replacement. Some irregular replacement deposits occur in shattered granite.

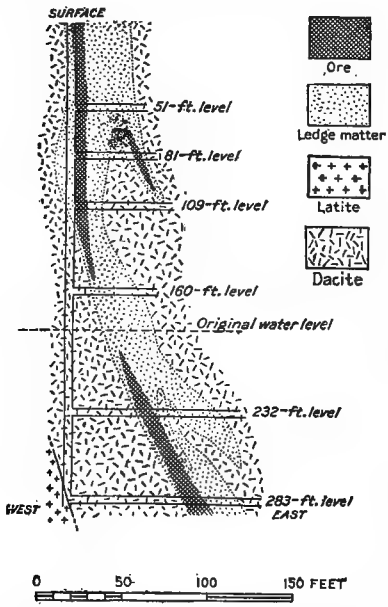


FIG. 242.—Cross-section of January mine, Goldfield, Nev. (*After Ransome, U. S. Geol. Survey.*)

Calaverite is the chief primary constituent of the ores; native gold is rarely present in the unoxidized ores. Pyrite is widely distributed; tetrahedrite, stibnite, sphalerite, and

[1] PENROSE, R. A. F.: Mining Geology of the Cripple Creek District, Colorado. U. S. Geol. Survey *Sixteenth Ann. Rept.*, part 2, pp. 123–209, 1895.

LINDGREN, WALDEMAR and RANSOME, F. L.: Geology and Gold Deposits of the Cripple Creek District, Colorado. U. S. Geol. Survey *Prof. Paper* 54, pp. 167–168, 1906.

molybdenite are sparingly present. The gangue is made up of quartz, fluorite, adularia, carbonates, some sulphates, and other minerals. Some of the deposits were workable at the surface, but the placers formed are of relatively little value.

Goldfield, Nevada.—The Goldfield district, Nevada,[1] is a low domical uplift of Tertiary lavas and lake sediments resting upon ancient granitic and metamorphosed sedimentary rocks. Erosion of the flat dome has exposed the pre-Tertiary rocks, and these are surrounded by wide zones of younger formations. Some of the later lavas were erupted after the dome had been elevated and truncated. The Tertiary rocks are mainly volcanic. Dacite occupies a considerable area east of Goldfield and is the principal country rock of the larger mines.

The region of the deposits is complexly fissured. The rocks, especially the dacite, have undergone extensive hydrothermal alteration, attended by the development of much alunite, kaolin, quartz, and pyrite. The deposits (Fig. 242) are related to fissures and were formed by replacement. They carry gold and some are exceptionally rich. Associated minerals are pyrite, marcasite, bismuthinite, famatinite (Cu_3SbS_4), goldfieldite (a cupric sulphantimonite) and a tellurium compound.

SILVER

MINERAL COMPOSITION OF SILVER DEPOSITS

Mineral	Percentage of silver	Composition
Silver	100.0	Ag
Cerargyrite	75.3	AgCl
Bromyrite	57.4	AgBr
Iodyrite	46.0	AgI
Argentite	87.1	Ag_2S
Pyrargyrite	59.9	Ag_3SbS_3 or $3Ag_2S.Sb_2S_3$
Proustite	65.4	Ag_3AsS_3 or $3Ag_2S.As_2S_3$
Stephanite	68.5	Ag_5SbS_4 or $5Ag_2S.Sb_2S_3$
Polybasite	75.6	Ag_9SbS_6 or $9Ag_2S.Sb_2S_3$
Pearceite	78.4	Ag_9AsS_6 or $9Ag_2S.As_2S_3$
Tetrahedrite	Variable	$4Cu_2S.Sb_2S_3$ or $4(Cu_2Ag_2)S.Sb_2S_3$
Tennantite	Variable	$4Cu_2S.As_2S_3$ or $4(Cu_2Ag_2)S.As_2S_3$
Tellurides		

[1] RANSOME, F. L.: The Geology and Ore Deposits of Goldfield, Nev. U. S. Geol. Survey *Prof. Paper* 66, p. 27, 1909.

Silver forms many stable compounds. Of these only a few, the more common ones, are mentioned above. The silver ores are generally more complex than those of gold and more difficult to treat. Silver in many deposits occurs in an undetermined state intergrown with other minerals. Thus galena is commonly argentiferous, and sphalerite, pyrite, or other sulphides may carry enough silver to make it the principal consideration in the ore. Nearly all copper deposits carry some silver, and in smelting much of it is recovered.

Most deposits of silver are veins and related deposits, formed mainly at moderate and shallow depths. Sulphide deposits containing silver are readily enriched by weathering. The metal goes into solution in the presence of ferric sulphate and sulphuric acid[1] and, as shown by Bastin,[2] can be precipitated by many sulphides as native metal. If chlorides are present horn silver, which is relatively insoluble, is precipitated and commonly accumulates near the surface (Fig. 243). In depth silver sulphide, argentite, is precipitated by hydrogen sulphide and by many metallic sulphides. If the deposits contain antimony or arsenic, the silver minerals containing those metals and sulphur are deposited, among them pyrargyrite, proustite, stephanite, and polybasite. In 1920 the United States produced 56,564,504 troy ounces of silver valued at $57,420,325.

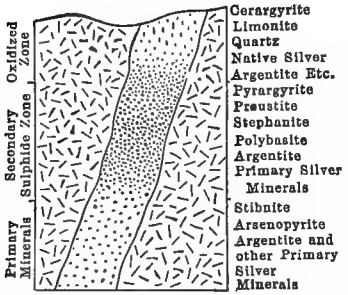


FIG. 243.—Ideal section showing distribution of minerals in a silver deposit that has been superficially altered.

Cobalt, Ontario.—Cobalt,[3] in the Nipissing district, northern

[1] COOKE, H. C.: The Secondary Enrichment of Silver Ores. *Jour. Geol.*, vol. 21, p. 17, 1913.

[2] PALMER, CHASE and BASTIN, E. S.: Metallic Minerals as Precipitants of Silver and Gold. *Econ. Geol.*, vol. 8, p. 140, 1913.

GROUT, F. F.: On the Behavior of Gold Acid, Sulphate, Solutions of Copper, Silver, and Gold with Alkaline Extracts of Metallic Sulphides. *Econ. Geol.*, vol. 8, pp. 407–433, 1913.

RAVIOZ, L. G.: Enrichment of Silver Ores. *Econ. Geol.*, vol. 10, pp. 368–392, 1915.

[3] MILLER, W. G.: The Cobalt-Nickel Arsenides and Silver Deposits of Temiskaming, 3d ed. Ontario Bur. Mines *Rept.*, vol. 16, part 2, 1908—4th ed. *Idem.*, vol. 19, part 2, 1913.

Ontario, is at present the most productive silver-bearing district in North America.

It is on the great ancient peneplain which extends over much of Ontario and the surrounding region. The recent glaciation is clearly evident, but drift is generally thin or absent.

The basement rocks are the Keewatin series, a complex of metamorphosed basic igneous rocks, usually known as greenstones, which includes also some rock of sedimentary origin. The eroded surface of the Keewatin is overlain by Huronian conglomerates, graywacke, and other metamorphosed sedimentary rocks. A quartz diabase sill some 500 feet thick was intruded into both Huronian and Keewatin rocks. This dips about 17°S.

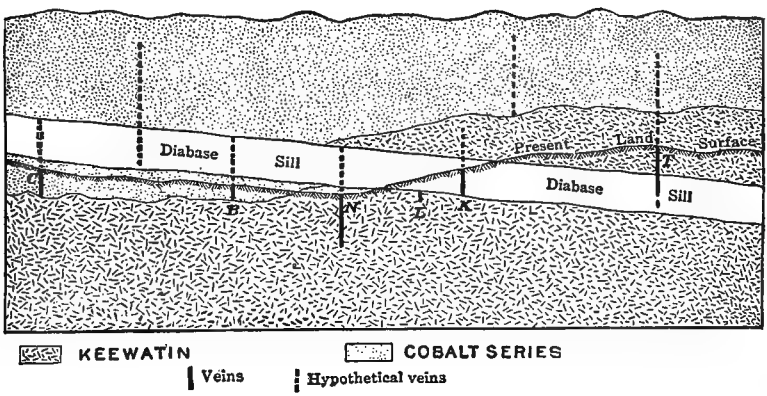


FIG. 244.—Generalized vertical section through the productive part of the Cobalt area, Ontario. (*After Miller.*)

The section shows the relations of the Nipissing diabase sill to the Keewatin and Cobalt series and to the veins. The eroded surface is restored in the section. The sill is less regular than the illustration shows it to be. *B* and *C* represent a large number of veins that are in the fragmental rocks (Cobalt series), in the footwall of the eroded sill. *N* represents a type of vein, such as No. 26 on the Nipissing, in the Keewatin below the eroded sill, and *L* a type such as one under Peterson Lake, in the Keewatin footwall, but not extending upward into the sill; *K*, a vein in the sill itself, such as No. 3 on the Kerr Lake property; *T*, a vein, such as that on the Temiskaming or Beaver properties, in the Keewatin hanging wall and extending downward into the sill.

The deposits are short, narrow veins, very numerous and rich. The more productive deposits are in the Huronian near the diabase sill, or they were below the footwall of the sill before the sill was eroded (Fig. 244). The deposits are probably genetically related to the diabase.

The principal sulphides of earlier age include smaltite, cobaltite, chloanthite, and bismuth sulphide, with some arsenopyrite

and tetrahedrite. Pyrite, galena, and sphalerite are present in the wall rock near the vein. The silver occurs as native metal, proustite, pyrargyrite, dyscrasite, and argentite. The gangue minerals include calcite and quartz.

The zone of oxidation is shallow or lacking, but certain rich superficial deposits, a few feet thick, are directly connected with the zone of weathering. In this zone smaltite and cobaltite have been largely altered to secondary minerals or leached out. Erythrite and annabergite are characteristic minerals of this zone.

Extending downward 200 or 300 feet or more below the surface are rich silver minerals, largely in veinlets in earlier sulphides. The minerals of the veinlets include native silver, argentite, and calcite. Some writers have attributed these richer silver ores to processes of sulphide enrichment, but Miller is inclined to the belief that this feature of the genesis has been too much emphasized.

Boulder-Leadville Belt, Colorado.—Lying 30 or 40 miles west of Denver, Colorado, and extending from Boulder southwest to

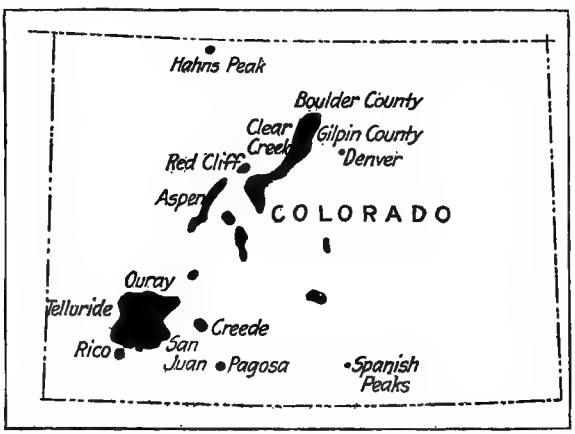


Fig. 245.—Sketch showing metallized areas in Colorado. (*After Spurr and Garrey, U. S. Geol. Survey.*)

Leadville, a distance of about 80 miles (Fig. 245) is one of the most richly mineralized belts in North America. This belt is occupied by pre-Cambrian schists, gneisses, granites, and other igneous rocks overlain by Paleozoic and Mesozoic sedimentary rocks. It contains many porphyry dikes, sills, and stocks, which are believed to be of late Cretaceous or early Tertiary age. Closely associated with the intrusive rocks and probably of about

the same age are numerous deposits containing silver, gold, lead, and other metals. In the igneous rocks and schists the principal deposits are normal veins. In the limestones irregular replacement and bedding-plane deposits predominate.

The ores vary from place to place but normally contain a fairly high proportion of sulphides, including pyrite, sphalerite, galena, chalcopyrite, and tetrahedrite. The gangue is quartz and some deposits contain also carbonates and barite. In the wall rock near the veins sericite and carbonates occur. There is very little contact metamorphism near the intruding rocks, and no andradite-amphibole border zones are developed. The deposits have been formed mainly at moderate depths, probably between 1 and 2 miles below the surface; those formed at the greater depths are most abundant in the southwestern part of the area. Near Georgetown[1] and in the Idaho Springs district, the deposits are closely related to certain igneous dikes.

Leadville.—Leadville[2] stands about 10,000 feet above sea level, on a high terrace at the foot of a spur of the Mosquito Range. The district is one of the most productive in the West and has yielded large quantities of lead and silver, considerable gold, zinc, and copper, and some iron, manganese, and bismuth. The district is an area of limestone, shale and quartzite intruded by porphyry which occurs mainly as sheets.

The most valuable deposits are found in Carboniferous limestone at or near its contact with an overlying porphyry. Thus

[1] Spurr, J. E., Garrey, G. H. and Ball, S. H.: Economic Geology of the Georgetown Quadrangle, Colorado. U. S. Geol. Survey *Prof. Paper* 63, p. 145, 1908.

Bastin, E. S., and Hill, J. M.: Economic Geology of Gilpin County and Adjacent Parts of Clear Creek and Boulder Counties, Colorado. U. S. Geol. Survey *Prof. Paper* 94, pp. 190–280, 1917.

Butler, G. M., Hoskin, A. J. and Patton, H. B.: Geology and Ore Deposits of the Alma District. Colo. Geol. Survey *Bull.* 3, pp. 1–284, 1912.

[2] Emmons, S. F.: Geology and Mining Industry of Leadville, Colo. U. S. Geol. Survey *Mon.* 12, 1886.

Emmons, S. F., and Irving, J. D.: The Downtown District of Leadville, Colo. U. S. Geol. Survey *Bull.* 320, 1907.

Argall, Philip: The Zinc Carbonate Ores of Leadville. Min. Mag., vol. 10, pp. 282–288, 1914.

Ricketts, L. D.: "The Ores of Leadville," Princeton, 1883.

Blow, A. A.: The Geology and Ore Deposits of Iron Hill, Leadville, Colo. Am. Inst. Min. Eng. *Trans.*, vol. 18, pp. 145–181, 1890.

Butler, G. M.: Some Recent Developments at Leadville. *Econ. Geol.*, vol. 7, pp. 315–323, 1912; vol. 8, pp. 1–18, 1913.

the ore bodies constitute sheets, the upper surfaces of which, being formed by the bases of the porphyry bodies are comparatively regular, while the lower surfaces are ill-defined and irregular, there being a gradual transition from ore to limestone. The ore extends to varying depths below the surface, occupying in places the entire thickness of the "Blue" limestone. Other deposits include, however, steeply dipping veins, some of them in fault fissures, and irregular masses or sheets in limestone near the porphyries (Fig. 246).

The most valuable ore consists of argentiferous galena and its secondary products, cerusite and cerargyrite. Lead is found also as anglesite and pyromorphite and occasionally as oxide. The gangue minerals include quartz, chert, barite, siderite, and

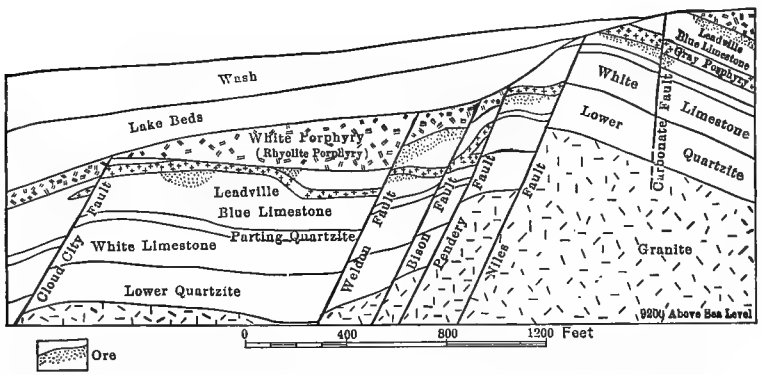


Fig. 246.—Geologic section of the Downtown district, Leadville, Colo. (*After Emmons and Irving.*)

clay, the clay being commonly charged with iron and manganese oxides or with sulphates.

Alteration products of mixed pyrite and galena ore include limonite, jarosite, anglesite, and pyromorphite. Manganiferous siderite on oxidation yields manganese oxides.

Gold occurs in small flakes. Other minerals are zinc blende, calamine, arsenic and antimony (probably as sulphides), wulfenite, copper carbonate and silicate, and bismuth sulphide. Nodules of galena surrounded by lead carbonates are locally numerous in the oxidized zone.

In depth the ores consist of pyrite, sphalerite, and galena, with some chalcopyrite and other minerals.

Recently large bodies of iron-stained smithsonite and of monheimite have been found in the oxidized zones below lead-carbonate ores.

San Juan Region, Colorado.—The San Juan region,[1] in southwestern Colorado, embraces a lofty plateau from which rise rugged mountains. The central group is termed the San Juan Mountains, and on its border are the Rico, La Plata, Engineer, Needle, and other mountains and mountain groups. The rocks in this region range in age from pre-Cambrian to Recent, and all the great subdivisions are represented. The dominant structural feature is a great dome, on the margin of which are smaller domes and laccoliths. Intruding the sedimentary rocks and lavas and locally cutting across the laccolithic sheets are great bodies of diorite and monzonite, which occur principally as stocks. Volcanic rocks predominate especially in the central, more elevated part of the area. The volcanic activity, which probably began in early Tertiary time, appears to have continued through most of that period. At several places within the region are hot springs, which are regarded as features of a declining volcanic era.

After the latest volcanic rocks were erupted the region was complexly faulted. Some of the faults are mineralized, among them the Amethyst fault at Creede, which carries the most productive silver deposit in the San Juan region.

The ore deposits of the San Juan region are in the main veins and related deposits. The central part of the region is noted for strong, persistent veins with bold outcrops. Many of them may easily be followed on the surface for thousands of feet. Not all the deposits are simple veins. The pipe-like deposits on Red Mountain, between Silverton and Ouray, and the ribbons of ore replacing limestone at Rico and Ouray are noteworthy. Nearly all the deposits exhibit features of veins formed at moderate depths. Among them the Camp Bird, Liberty Bell, Smuggler Union and Tomboy in the high country between Ouray and Telluride. A few veins near Rico and Ouray and in the Tellu-

[1] Cross, Whitman and Howe, Ernest: U. S. Geol. Survey *Geol. Atlas*, Silverton folio (No. 120), 1905.

Cross, Whitman: U. S. Geol. Survey *Geol. Atlas*, Telluride folio (No. 57), 1899.

Ransome, F. L.: A Report on the Economic Geology of the Silverton Quadrangle, Colorado. U. S. Geol. Survey *Bull.* 182, pp. 1–265, 1901.

ride region contain specularite, magnetite, and other minerals normally found at great depths, and a few deposits appear to have been formed at shallow depths. At least two periods of vein formation are indicated. The principal metals produced are silver, gold, and lead, with some zinc and a little copper. The production of the region, including Creede, is estimated at more than $200,000,000.

Park City, Utah.—Park City[1] is about 25 miles southeast of Salt Lake, Utah. The sedimentary rocks of the district are of Pennsylvanian, Permian (?), Triassic, Jurassic (?), and Eocene age and consist of quartzite, limestone, shale, and sandstone. The Eocene rocks grade upward into andesite tuff and are overlain by andesite. The sedimentary rocks are intruded by dikes, sills, stocks, and laccolithic masses of quartz diorite and quartz diorite porphyry.

The intrusion of igneous rocks was attended by the development of zones of garnet in limestone around the igneous bodies, and in some of these zones there are chalcopyrite, sphalerite, and other ores. The principal ore bodies, however, are not garnetiferous.

The deposits are replacement veins in limestone, quartzite, and porphyry. Although the limestones are interstratified with extensive beds of shale, the shale is not mineralized. The lode deposits are extensive, strong, and valuable. They lie mainly in the Ontario, Daly West, Silver King, and Kearns-Keith fissure zones. The deposits yield silver and lead.

The earliest deposits were formed as large tabular bodies parallel to the beds. Later the great crosscutting fissure zones were formed and metallized. Some of these cut across the earlier deposits, and at many places ore shoots of contemporaneous age make out from them parallel to the beds. Thus there are bedding-plane deposits of two periods of metallization, but all the deposits are believed to be genetically related to intrusive rocks, for they are not found more than a few hundred feet from the intrusives.

The ore minerals are galena, pyrite, chalcopyrite, sphalerite, tetrahedrite, and the usual oxidation products. The gangue minerals are quartz, jasper, fluorite, calcite, and rhodochrosite.

[1] BOUTWELL, J. M.: The Geology and Ore Deposits of the Park City District, Utah, with Contributions by L. H. WOOLSEY. U. S. Geol. Survey *Prof. Paper* 77, 1912.

Where porphyry lies along the walls it is silicified and sericitized and contains pyrite. The bedded ores are generally richer than the lode ores.

Tintic, Utah.—The Tintic district,[1] in central Utah, yields complex smelting ores containing gold, silver, lead, and copper. Recently valuable zinc deposits have been developed. The area is occupied by a thick series of Paleozoic quartzite, slate, limestone, and sandstone, which are overlain by Tertiary rhyolite and andesite. These rocks are intruded by great masses of monzonite and by basalt dikes, and an andesite, equivalent to the monzonite, caps the rhyolite. The rocks are folded and extensively fractured and faulted.

After the folding and erosion of the Paleozoic sedimentary rocks, volcanic material was poured out, the earlier rhyolitic lava filling deep canyons. The more compact igneous and sedimentary rocks were fissured, and ores were deposited in them.

The ore deposits are (1) large fractured zones in sedimentary rocks, chiefly in the limestone; (2) veins in igneous rocks; and (3) contact-metamorphic deposits in sedimentary rocks near intrusive igneous rocks, mainly in limestone near monzonite.[2]

The primary ore minerals include pyrite, galena, enargite, chalcopyrite, and tennantite. The gangue includes quartz, barite, carbonates, chalcedony, and gypsum. Oxidation products are limonite, hematite, anglesite, cerusite, cerargyrite, native sulphur, jarosite, copper carbonates, cuprite, native copper, and a large number of rare arsenic compounds that have resulted from the decomposition of enargite. Chalcocite and bornite become increasingly abundant in the lower parts of the oxidized zone.

Valuable oxidized zinc ores have recently been developed.

[1] Tower, G. W., Jr. and Smith, G. O.: Geology and Mining Industry of the Tintic District, Utah. U. S. Geol. Survey *Nineteenth Ann. Rept.*, part 3, pp. 603–767, 1899.

Loughlin, G. F.: The Oxidized Zinc Ores of the Tintic District, Utah. *Econ. Geol.*, vol. 9, pp. 1–19, 1914.

Lindgren, Waldemar and Loughlin, G. F.: Geology and Ore Deposits of the Tintic Mining District, Utah. U. S. Geol. Survey *Prof. Paper* 107, pp. 1–282, 1919.

Crane, G. W.: Geology of the Ore Deposits of the Tintic Mining District. Am. Inst. Min. Eng. *Trans.*, vol. 54, pp. 342–355, 1917.

[2] Subordinate importance.

Apparently they have been deposited by ground water that dissolved zinc from the sulphide bodies and migrated into the limestone wall rock. Zinc sulphate reacting on lime carbonate has precipitated smithsonite.

Comstock Lode, Nevada.—The Comstock lode (Washoe district), Nevada, about 20 miles southeast of Reno had produced over $380,000,000 in gold and silver, which is more than the production of any other precious-metal camp in the United States. About 60 per cent. of this sum is in silver and 40 per cent. in gold. Production has declined greatly, however, and is now less than $500,000 annually. The workings in depth are hot. Large volumes of hot sulphate water (170°F.) rise from the deep workings and greatly hinder mining.

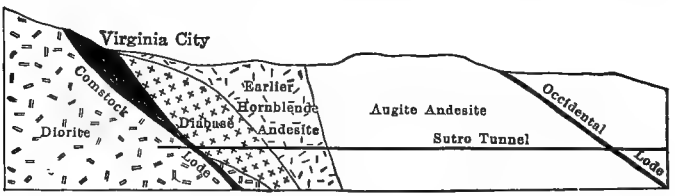


FIG. 247.—Section through Comstock lode, Nevada, on Sutro tunnel. Black is quartz and vein matter. (*After Becker, U. S. Geol. Survey.*)

The lode[1] lies along a broad fault in late Tertiary rocks (Fig. 247). It strikes a few degrees east of north and dips about 45° E. The footwall is diorite, and the hanging wall is mainly diabase. The hanging wall was apparently shattered as it fell, and many nearly vertical fractures in it join the lode in depth.

The country rock is greatly altered by hydrothermal processes. Chlorite, sericite, and pyrite are developed, and probably secondary orthoclase. Along the fault is a body of quartz and vein matter several hundred feet wide. The ore shoots are found here and there in this quartzose material, and some of them make off in the hanging wall along secondary fractures. Much of the quartz is barren. The ore is composed of native gold, native silver, argentite, stephanite, and rich galena, with a little pyrargyrite, polybasite, horn silver, and sternbergite. Other minerals

[1] KING, CLARENCE and HAGUE, J. D.: The Comstock Lode, Mining Industry. U. S. Geol. Expl. *Fortieth Par. Rept.*, vol. 3, pp. 11–96, 1870.

BECKER, G. F.: Geology of the ComstockLode and the Washoe District. U. S. Geol. Survey *Mon.* 3, pp. 1–422, 1882.

REID, J. A.: The Structure and Genesis of the Comstock Lode. California Univ. Dept. Geol. *Bull.*, vol. 4, pp. 177–199, 1905.

are iron and copper pyrites and zinc blende. The gangue is quartz with some calcite. Oxidation of the ore yields abundant manganese oxide, probably from the calcite.

After deposition much of the ore was fractured and enriched.

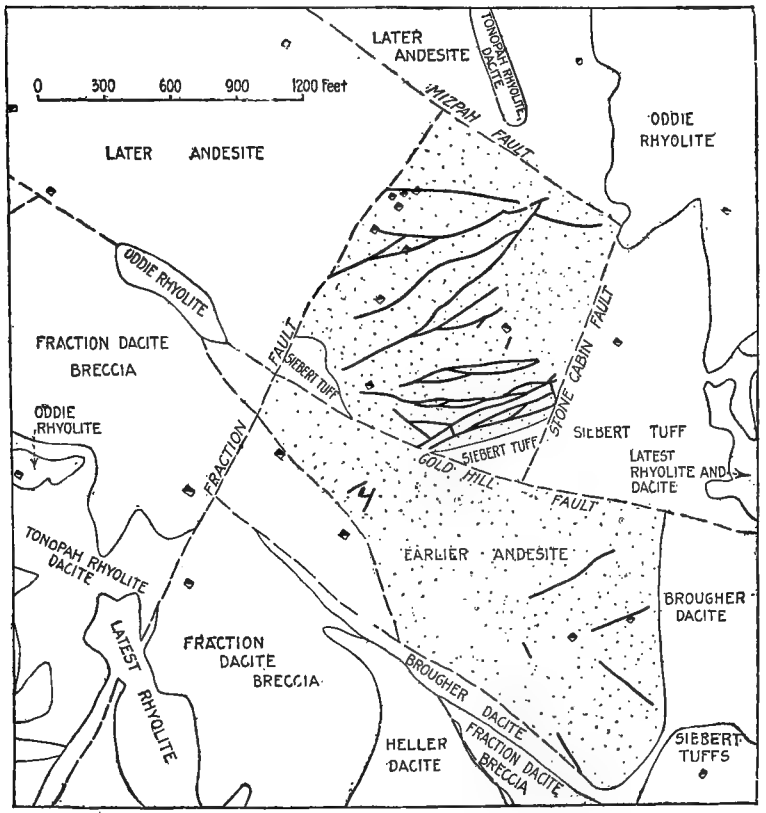


FIG. 248.—Geologic sketch map of part of Tonopah district, Nevada. (*After Spurr, U. S. Geol. Survey.*)

Tonopah, Nevada.—Tonopah[1] is in the desert region of western Nevada, about 160 miles southeast of Reno. All the rocks near

[1] SPURR, J. E.: Geology of the Tonopah Mining District, Nevada. U. S. Geol. Survey *Prof. Paper* 42, 1905; Geology and Ore Deposition at Tonopah, Nev. *Econ. Geol.*, vol. 10, p. 713, 1915.

BASTIN, E. S. and LANEY, F. B.: The Genesiso f the Ores at Tonopah, Nev. U. S. Geol. Survey *Prof. Paper* 104, pp. 1–50, 1918.

BURGESS, J. A.: Geology of the Producing Part of the Tonopah District. *Econ. Geol.*, vol. 4, p. 681, 1909.

Tonopah are of Tertiary age, probably Miocene and later, and all are eruptive except a series of water-laid tuffs.

The first eruption of the volcanic period produced the Mizpah trachyte (formerly called the Earlier andesite). Later an andesite (somewhat more basic and formerly called the Later andesite) was formed. Subsequently rhyolite and dacite were erupted and produced the volcanoes whose necks, left in relief by the erosion of the surrounding softer material, now form the hills around Tonopah.

The principal mineral veins occur in the Mizpah trachyte and do not extend into the overlying rocks (Fig. 248). They carry silver and some gold.

These veins have been formed, chiefly by replacement, along sheeted zones. The mineralization was probably caused by hot ascending waters immediately after the earlier trachyte eruptions.

The Mizpah vein is for the most part oxidized to a depth of 700 feet. The oxidized ore contains limonite and manganese dioxide, with horn silver and bromides and iodides of silver. The oxidized ore from the outcrop down is, according to Spurr, a mixture of original sulphides and selenides, together with secondary sulphides, chlorides, and oxides. At a depth of 500 feet in the Montana Tonopah mine good crystals of argentite, polybasite, and chalcopyrite have been formed freely in cracks and druses of the sulphide ore. These minerals are later than the massive ore. Pyrargyrite is formed in cracks in the oxidized ore, and some argentite fringes minute particles of horn silver as if secondary to it.

CHAPTER XX

ZINC AND LEAD

ZINC

Mineral	Percentage of zinc	Composition
Goslarite	22.6	$ZnSO_4 \cdot 7H_2O$
Smithsonite	52.0	$ZnCO_3$.
Calamine	54.2	$Zn_2H_2SiO_5$ or $2ZnO \cdot SiO_2 \cdot H_2O$
Willemite	58.5	Zn_2SiO_4.
Hydrozincite	60.0	$ZnCO_3 \cdot 2ZnO_2H_2$ or $3ZnO \cdot CO_2 \cdot 2H_2O$
Zincite	80.3	ZnO
Franklinite	16.0	$(Fe,Zn,Mn)O \cdot (Fe, Mn)_2O_3$
Sphalerite (zinc blende)	67.0	ZnS
Wurtzite	67.0	ZnS

Nearly all deposits of zinc ore contain sphalerite or are the oxidation products of sphalerite ores. The deposits include veins

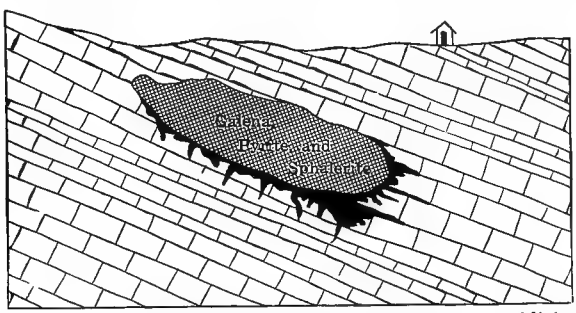


FIG. 249.—Ideal diagram showing a mass of sulphide ore oxidizing in limestone. The lead ore is partly ozidized but remains in place. By oxidation and leaching iron and zinc sulphates are formed and move downward. Zinc carbonate (black) is precipitated around the original ore body and in joints and bedding planes near it.

formed at all depths and contact-metamorphic deposits. Zinc deposits are formed also by cold solutions that dissolve zinc from the country rock in which it is sparingly present, and deposit it in openings or at other places where conditions are favorable for precipitation.

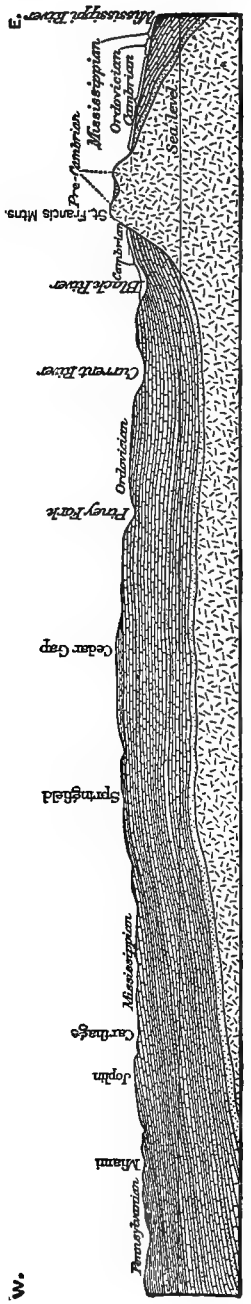


FIG. 250.—Geologic section of the Ozark uplift, Missouri. (*After Buckley.*)

Zinc sulphide oxidizes to the soluble zinc sulphate, and zinc minerals are readily dissolved by sulphuric acid. Zinc is precipitated from sulphuric acid solutions by carbonates. In limestone rich zinc carbonate deposits are found near sulphide ores that are oxidizing (Fig. 249). Calamine also is secondary. In depth zinc is precipitated as sulphides, both wurtzite and sphalerite being formed by secondary processes. Not all primary zinc deposits are sulphides; a noteworthy exception is presented by those of Franklin Furnace, New Jersey in which zinc occurs as primary oxides, and silicate—franklinite, zincite, and willemite.

The production of zinc in the United States in 1920 was 450,045 short tons, valued at $72,907,000. In 1921 prices and production declined.

Joplin Region.—The Joplin region, which is mainly in southwestern Missouri, extends into neighboring portions of Kansas and Oklahoma. The deposits have been known since 1850, and the mines have produced over 1,000,000 tons of lead concentrates and 6,000,000 tons of zinc concentrates. The ore in general is of low grade, and enormous tonnages are treated, especially of ore from the "sheet ground." Considering the nature of the deposits the low cost of mining in this region is noteworthy.

All the rocks[1] of the region are sedimentary. They dip south-

[1] BAIN, H. F.: Preliminary Report on the Lead and Zinc Deposits of the Ozark Region. U. S. Geol. Survey *Twenty-second Ann. Rept.*, part 2, pp. 23–228, 1901.

westward at very low angles away from the Ozark uplift (Fig. 250). The surface is a rolling prairie. Carboniferous rocks only are exposed. These are for the most part Mississippian, but here and there small remnants of Pennsylvanian rocks are found. The following formations are represented:

Cherokee formation (Pennsylvanian): Shale, sandstone, and coal beds, top eroded; at some places it rests on Carterville, at others on Boone chert; at many places entire formation has been removed by erosion.	0 to 150+
Unconformity.	
Carterville formation (Pennsylvanian): Shale and sandstone. Rests on eroded surface of Boone; not everywhere present. .	0 to 50
Unconformity, marked by an erosion surface of the Boone with valleys and ridges.	
Boone formation (Mississippian): A thick cherty limestone. It contains the Grand Falls chert member, from 15 to 120 feet thick. The top is an erosion surface subsequently covered by Pennsylvanian shale and sandstone. The Boone is the principal ore-bearing formation. The "sheet ground" is in the Grand Falls chert.	145 to 485
Pre-Boone limestone, sandstone, and locally shale.	

During the two periods of erosion represented by the unconformities above and below the Carterville formation the Boone limestone was deeply trenched and a topography characterized by underground drainage was developed.[1] Caves were formed, and limestone sinks were numerous. The country was near sea level, and solution greatly exceeded stream erosion. On the surface there accumulated great bodies of residual chert. This chert is typically shown in the Granby district, where it has been termed the "Granby" formation by Buckley and Buehler. The "Granby" and Boone were covered by the Carterville. Later the Carterville was eroded in places, and the Cherokee was deposited on the eroded surface of the Boone or, where it was pres-

[1] Smith, W. S. T., and Siebenthal, C. E.: U. S. Geol. Survey *Geol. Atlas*, Joplin District Folio (No. 148), 1907.

Buckley, E. R., and Buehler, H. A.: The Geology of the Granby Area. Mo. Bureau of. Geol. and Mines, vol. 4, 2d ser., 1909.

Haworth, Erasmus: Relation between the Ozark Uplift and Ore Deposits. Geol. Soc. America *Bull.*, vol. 11, pp. 231–240, 1900.

Siebenthal, C. E.: Origin of the Zinc and Lead Deposits of the Joplin Region, Missouri, Kansas, and Oklahoma. U. S. Geol. Survey *Bull.* 606, 1915.

Adams, G. I.: Zinc and Lead Deposits of Northern Arkansas. U. S. Geol. Survey *Prof. Paper* 24, pp. 1–118, 1904.

ent, on the Carterville. After the Boone had been buried below later beds it contained, at and near its top, water channels, such as solution cavities and buried talus of chert. The cavities and breccia were later cemented with ores.

The principal ore minerals are sphalerite and galena and their oxidation products. A little cadmium is present, but practically no silver. The ore is believed to have been deposited by cold underground water. The beds dip at low angles from the Ozark uplift, and Siebenthal regards the solutions that deposited the ore as circulating at considerable depth under artesian conditions. On the other hand, Buehler and his associates of the Missouri Geological Survey believe that the metalliferous waters moved downward.

Wisconsin Region.—In the upper Mississippi Valley, in southwestern Wisconsin, northwestern Illinois, and northeastern Iowa, are numerous deposits of zinc and lead.[1] The rocks of this area are limestone, sandstone, and shale. They dip very gently to the southwest, and in places there are small shallow synclines. The rocks are fissured and heavily jointed, but there are no great faults in the region. Outcrops of igneous rocks likewise are lacking.

The rock section is shown below. The ores are principally in the Galena limestone, though some are in the Platteville limestone and some in the Maquoketa shale. Most of the workable deposits are near the base of the Galena, though some are in the upper part.

	Feet
Quaternary: Alluvium, terrace deposits, loess, residual clays	5 to 70
Silurian: Niagara dolomite	150
Ordovician:	
Maquoketa shale	160
Galena dolomite	240
Platteville limestone and dolomite	55
St. Peter sandstone	80
Shakopee dolomite	50
New Richmond sandstone	10 to 40
Oneota dolomite	200
Cambrian: Potsdam sandstone, with minor shale and dolomite	800
Pre-Cambrian: Quartzite with various igneous rocks.	

[1] GRANT, U. S.: Lead and Zinc Deposits of Wisconsin. Wis. Geol. Survey *Bull.* 9, 1903.

BAIN, H. F.: Zinc and Lead Deposits of the Upper Mississippi Valley. U. S. Geol. Survey *Bull.* 294, 1906

COX, G. H.: Leads and Zinc Deposits of Northwestern Illinois. Ill. Geol. Survey *Bull.* 21, 1914.

The generalized section at the main ore horizon is as follows:

	Feet
Dolomitic limestone (Galena), free from chert	50
Oil rock (Galena)	½ to 6
Shale or blue clay, called the "clay seam" (Platteville)	½ to 4
Brittle limestone, "glass rock" (Platteville).	
Magnesian limestone (Platteville).	

The shale or clay seam is at the top of the Platteville. The oil rock is an impure shaly limestone rich in organic matter, which consists chiefly of microscopic algæ. The oil rock, according to R. T. Chamberlin, on heating yields a gas which contains much H_2S and CH_4.

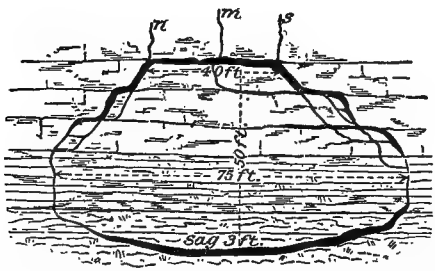


FIG. 251.—Section showing flats and pitches in the Roberts mine, Linden, Wis. *n*, *m*, *s*, are north, middle and south crevices. (*After T. C. Chamberlin.*)

The ore deposits are in "crevices," in "runs," disseminated in beds, and in "flats and pitches." Certain beds appear to be especially favorable to concentration of the ore, and where these are cut by crevices, flat-lying irregular ribbons of ore are developed at and near the intersections. Such ore bodies are termed "runs."

The ore in the "flats" follows the flat beds, and the ore in the "pitches" follows crevices that pitch or dip away about 45° from either side of the vertical crevices (Fig. 251). The pitches in a deposit join at the end, making in plan a long, slender ellipse where they intersect the oil rock. The form of the whole body has been compared by Chamberlin to the domestic flatiron. As shown by Grant, this is a very common structural type, and frequently the interior of the ellipse is filled with low-grade dis-

seminated ore, so that long, relatively narrow masses are worked. Deposits that are largely workable are commonly as much as 1,000 feet long, 75 feet wide, and 40 or 50 feet high.

The genesis of these deposits, as stated by Chamberlin, Grant, and Bain, is essentially as follows: The lead, zinc, and iron were originally deposited on the sea bottom at the time the Galena dolomite was laid down. The metals were probably in solution as sulphates and chlorides and were reduced by organic matter to sulphides at the time of their deposition. Later, when the beds, containing small amounts of metals, were elevated and the Maquoketa shale was removed, a more active circulation was established.

The ores are composed of sphalerite, galena, marcasite, and calcite. As shown by Grant, the deposits are in shallow synclines. The oil rock is believed to have been thicker in gentle depressions in the ocean floor. As a result of the loss of hydrocarbon gases the oil rock shrank, and as a result of shrinking the overlying beds settled and were fractured, forming the fissures for flats and pitches. The solutions which had dissolved zinc and lead from surrounding beds entered the cracks and deposited the metals, precipitation being probably aided by gases escaping from the oil rock. According to Grant, the metals originally were in the Galena dolomite, but Cox believes that they were derived in part from the Maquoketa shale.

Eastern Tennessee.—In eastern Tennessee zinc deposits are found at many places, but the larger deposits are between Knoxville and Morrison. The ore occurs as sphalerite and oxidation products and is found principally in the Knox dolomite. The zinc is of unusual purity and commands a premium in the market. The ore contains little pyrite, and oxidation has extended only to shallow depths.

Franklin Furnace, New Jersey.—The Franklin Furnace district is in Sussex County, New Jersey, about 50 miles northwest of Jersey City. Although discovered as early as 1650, the deposits were not actively exploited until 1860. The larger part of the ore is concentrated, partly by magnetic processes, but a considerable amount is smelted directly. The residuum obtained from smelting some of the zinc ores carries 12 per cent. of manganese and 40 per cent. of iron. Much of this material is utilized for the manufacture of spiegeleisen, a product added to iron in making high-grade steel.

The rocks of the Franklin Furnace area[1] are pre-Cambrian gneiss and limestone and Cambrian limestone and quartzite.

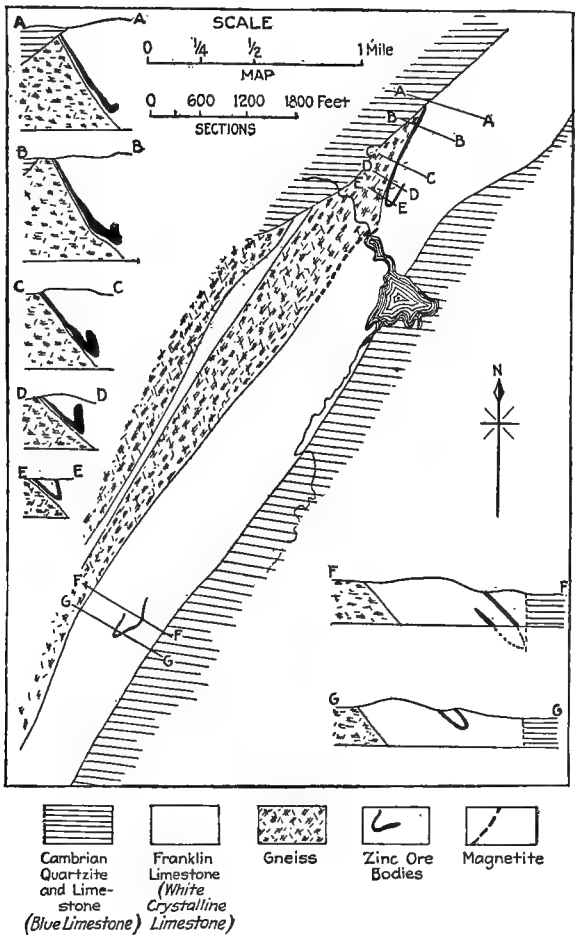


FIG. 252.—Geologic map and sections of Franklin Furnace region, New Jersey. (*Based on maps by A. C. Spencer, U. S. Geol. Survey.*)

The ore deposits are in the southwest end of a band of limestone that extends northeastward 22 miles into Orange County,

[1] SPENCER, A. C., KUMMEL, H. B., WOLFF, J. E., SALISBURY, R. D. and PALACHE, CHARLES: U. S. Geol. Survey *Geol. Atlas*, Franklin Furnace folio (No. 161), 1908.

SPENCER, A. C.: The Mine Hill and Sterling Hill Zinc Deposit of Sussex County, New Jersey. N. J. State Geologist *Ann. Rept.* for 1908, pp. 23–52, 1909.

New York (Fig. 252). Both limestone and gneiss are bounded by later Cambrian sediments. The main deposits are at Mine Hill and at Sterling Hill, about 2 miles apart. Both are spoon-shaped, or synclinal, and pitch about 20° NE. The ore layer is from 1 to 100 feet thick, and the total length of the "keel" of the syncline at Mine Hill is 3,500 feet. The Sterling Hill deposit is a great mass of low-grade zinc-bearing material 250 feet wide.

The ore minerals are unusual species: franklinite constitutes 50 per cent. of the ore, willemite 20 to 30 per cent., and zincite about 4 per cent. Other minerals are calcite, tephroite, zinc pyroxene, zinc spinel, zinc garnet, and axinite. Still other minerals, including sphalerite, have been deposited locally, especially near pegmatite veins that cross the ore bodies here and there.

The zinc deposits grade into limestone and doubtless were formed by replacement of limestone .

Butte, Montana.—The Butte district (see page 414) is one of the largest producers of zinc in the United States—a distinction only recently achieved. Most of the zinc ore comes from the Rainbow lode, which lies north of the copper deposits. The deposits are replacement veins and fractured zones, locally over 100 feet wide. The minerals include sphalerite, pyrite, galena, rhodochrosite, rhodonite, and quartz. Appreciable quantities of silver are present. Chalcopyrite, bornite, chalcocite, and other copper sulphides typical of the copper veins are found locally in the zinc deposits. Like the copper deposits of the Butte district, the zinc deposits appear to have been formed at intermediate depths by deposition from ascending hot waters genetically related to igneous activities.

A noteworthy feature of these deposits is the absence of carbonates and silicate of zinc in the zone of oxidation. This is probably due to thorough leaching by sulphuric acid generated by the oxidation of abundant pyrite.

Coeur d'Alene District, Idaho.—The Coeur d'Alene region of Idaho has for many years produced considerable zinc as a by-product of the concentration of lead ore, and recently some of the mines have encountered in depth large bodies of zinc ore. The Interstate-Callahan mine, one of the most productive zinc mines in the United States, is about 7 miles northeast of Wallace. The rocks of the area are pre-Cambrian quartzite and slate cut by monzonite and related igneous intrusives. The ore deposits

are veins. The ore minerals are sphalerite, galena, pyrite, and quartz. Little or no siderite is present. Considerable silver is contained in the galena concentrate.

LEAD

Mineral	Percentage of lead	Composition
Lead	100.0	Pb
Minium	90.6	$2PbO \cdot PbO_2$
Massicot	92.8	PbO
Plattnerite	86.6	PbO_2
Pyromorphite	76.3	$3Pb_3P_2O_8 \cdot PbCl_2$
Anglesite	68.3	$PbSO_4$
Cerussite	77.5	$PbCO_3$
Galena	86.6	PbS

Of the lead minerals galena, cerusite, and anglesite are the most abundant. The gangue minerals quartz, chert, siderite, and calcite are their common associates. Most galena ores connected genetically with igneous rocks contain silver or gold or both. The silver in argentiferous galena is commonly supposed to be present as silver sulphide. Some zinc is generally found in lead deposits, and in many zinc ores lead is a valuable by-product.

In its primary deposits lead is restricted to fewer classes than copper. Economic concentrations in igneous rocks are unknown. Some lead is found in contact-metamorphic deposits and in veins formed at considerable depths, but in only a few of these is it abundant. It is characteristically developed at moderate depths and in deposits formed by cold solutions in calcareous rocks.

Galena is the principal ore of lead. Its oxidation products are anglesite, cerusite, and pyromorphite and oxides. Lead minerals dissolve very slowly and enrichment takes place chiefly by removal of valueless material from lead deposits near the surface. The production of lead in the United States in 1920 was 476,849 short tons, valued at $76,296,000.

Southeastern Missouri.—The disseminated lead deposits of southeastern Missouri are about 50 miles south of St. Louis, in St. Francis and adjoining counties. These deposits produce about one-third of the lead of the United States.

The sedimentary beds are generally flat. They are cut by many faults that strike about northwest or northeast. Most of the ore is in the Cambrian Bonneterre limestone, especially near the base. The ore occurs as crystals and masses of galena disseminated in limestone or shale, as horizontal sheets along the bedding (Fig. 253), in small cavities or filling the small joints, and in shale and clay along faults. One ore body was 9,000 feet long, 5 to 100 feet thick, and 25 to 500 feet wide.

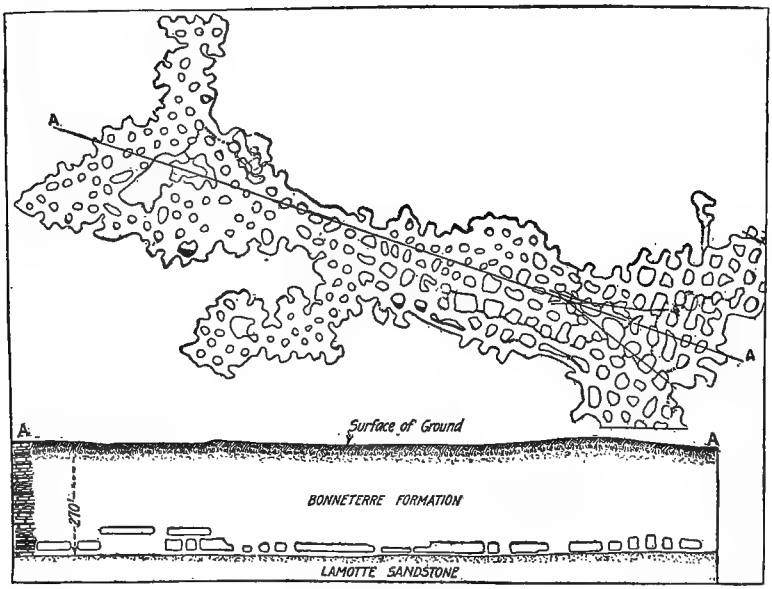


FIG. 253.—Mine map and cross-section of Desloge mine, St. Francis County, Missouri. (*After Buckley.*)

The limestone carries considerable organic material. The minerals of the deposits are galena with a little pyrite and at some places a little chalcopyrite or sphalerite. The gangue consists of calcite, chlorite, and a little quartz. The galena carries only about 2 ounces of silver to the ton of concentrates.

Both Buckley and Winslow attribute the metallization to ground water. The lead was formerly widely dispersed in the Bonneterre and probably in other formations. It was dissolved and concentrated in fractures through which the solutions moved, being precipitated on contact with reducing agents in limestone or associated shale beds.

Coeur d'Alene District, Idaho.—The Coeur d'Alene district[1] Idaho, is in a mountainous country near the Montana border. It produces about one-third of the lead output of the United States and considerable silver, copper, gold, and zinc.

The lead-silver ores, which carry about 8 per cent. of lead and 6 ounces of silver to the ton, are concentrated in the district to a product containing about 50 per cent. of lead, and the concentrates are shipped to western smelters where high-grade lead ores are in demand for smelting siliceous ores of silver and gold. The copper ores, though of low grade, receive favorable rates from smelters that use them for lining converters.

The Coeur d'Alene district is an area of pre-Cambrian quartzites and siliceous slates that are intruded by large masses of monzonite and monzonite porphyry, with dikes of diabase and lamprophyre.

The larger intrusive bodies are surrounded by aureoles of contact-metamorphosed sediments.

The rocks are separated into many small blocks by normal and reverse faults many of which trend nearly northwest.

The most valuable deposits of the district are lead-silver lodes, most of which strike northwest, in the direction of the principal faults. These lodes, however, do not occupy the principal fault planes. Only one, the Bunker Hill & Sullivan lode, is formed along a fault of notable displacement, and this fault is one of less than 200 feet throw. The deposits of this lode, though along the fault, are principally in subordinate hanging-wall fractures. The ores were formed partly by filling open spaces, but largely by replacement along zones of fissuring or shearing.

The ore minerals are galena, pyrite, chalcopyrite, and sphalerite, with some argentiferous tetrahedrite and stibnite. Siderite is the most abundant gangue mineral, but considerable quartz and a little barite are present. In depth pyrrhotite and magnetite appear, indicating conditions of the deep vein zone. Enrichment has probably been subordinate.

San Francisco Region, Utah.—The San Francisco region[2]

[1] RANSOME, F. L., and CALKINS, F. C.: The Geology and Ore Deposits of the Coeur d'Alene District, Idaho. U. S. Geol. Survey *Prof. Paper* 62, 1908.

FINLAY, J. R.: The Mining Industry of the Coeur d'Alene District, Idaho. Am. Inst. Min. Eng. *Trans.*, vol. 33, pp. 235–271, 1903.

HERSHEY, O. H.: Genesis of the Lead-Silver Ores in the Wardner District, Idaho. *Min. and Sci. Press*, vol. 104, pp. 750–753, 786–790, 725–727, 1912.

[2] BUTLER, B. S.: Geology and Ore Deposits of the San Francisco and Adjacent Districts, Utah. U. S. Geol. Survey *Prof. Paper* 80, 1913.

embraces the San Francisco and neighboring ranges in Beaver County, southwestern Utah. On account of the Cactus mine it is known at present principally as a copper district, but its past product was mainly lead and silver.

The sedimentary series consists of Paleozoic limestone, shales, and quartzite. These beds were covered by lava flows, chiefly latites, probably of early and middle Tertiary age. Both the sedimentary rocks and the lava flows are intruded by large bodies of quartz monzonite and by aplite and basic dikes. Contact-metamorphic deposits, with garnet, are developed near the quartz monzonite.

The ore deposits include (1) replacement deposits in fissures in the quartz monzonite, (2) replacement deposits in the limestone, including contact deposits and replacement deposits along fissures, and (3) replacement fissure deposits in the lavas.

The Horn Silver mine is on the largest deposit in the volcanic rocks. This deposit occurs along a fault that has thrown the lavas down against the Paleozoic limestone. The lavas are shattered along this fault, especially in the vicinity of minor cross faults. The ore deposits have been formed largely by replacement of the brecciated lava. The primary ore consists of pyrite, galena, sphalerite, and minor amounts of other metallic minerals in a gangue of quartz, sericite, and partly altered lava. In the oxidized zone the ores are characteristically sulphates, anglesite being the principal mineral in much of the lead ore. Complex sulphates, such as beaverite, plumbojarosite, and jarosite, are rather abundant, and the oxidized copper ore carries much brochantite. Zinc is not abundant in the oxidized ores. In the secondary sulphide zone the copper ore consists of covellite and chalcocite, partly or wholly replacing sphalerite, wurtzite, pyrite, and, to a slight extent, galena. Rich copper ores were mined to a depth of about 750 feet, and enrichment along favorable channels has extended deeper. The rich zinc ores of this mine are composed of sphalerite and wurtzite, together with other sulphides. The wurtzite is secondary, forming around cores of sphalerite, and the richer ores have resulted from the addition of the zinc in the wurtzite. Normally the zinc enrichment extends to greater depth than the copper enrichment, and secondary zinc sulphide has been replaced by secondary copper sulphides.

CHAPTER XXI

MISCELLANEOUS METALS

MANGANESE

Mineral	Percentage of manganese	Composition
Pyrolusite	60 to 63.0	MnO_2
Psilomelane	45 to 60.0	$Mn_2O_3\ x\ H_2O$
Wad	.....	Impure oxides
Manganite	62.4	$Mn_2O_3 \cdot H_2O$
Mallardite	19.9	$MnSO_4 \cdot 7H_2O$
Alabandite	63.1	MnS
Rhodochrosite	47.6	$MnCO_3$
Rhodonite	41.9	$MnSiO_3$
Tephroite (manganese olivine)	54.3	$2MnO \cdot SiO_2$
Spessartite (manganese garnet)	33.3	$3MnO \cdot Al_2O_3 \cdot 3SiO_2$

In its chemical relations and in its geologic occurrence manganese is closely related to iron. Its principal deposits are sedimentary beds and deposits formed by concentration in superficial zones. Oxides and subordinately carbonates of manganese are deposited in bogs in much the same way as bog iron ores are formed.

Manganese is dissolved and reprecipitated during weathering, somewhat more readily than iron.

Under conditions of weathering manganese oxides, like those of iron, tend to remain in the outcrop, and when other material is removed enrichment is accomplished. The gossans of some fissure veins have been worked for manganese. Some manganese is dissolved, however, and precipitated in depth, forming deposits of secondary oxide.

Parts of many sedimentary beds, as well as igneous rocks, and veins are rich enough to yield manganiferous ores by superficial alteration and concentration.

Manganese is used for making steel. Normally nearly all the manganese used in the United States is imported from Russia, India, and Brazil. When the World War began in 1914 imports from Russia stopped and those from India decreased. Prices rose, and there was an active effort to develop domestic supplies.

Manganese deposits were opened at scores of places in the United States. Nearly all of them, however, are of small extent, the total amount of high-grade ore at present developed being only about enough to meet one year's requirements.

The largest deposits of high-grade ore in the United States are those at Philipsburg, Montana, where, near an intruding mass of granite, rhodochrosite veins and irregular replacement deposits traverse limestones and shales.[1] These veins were formerly worked for silver. Near the surface and extending to depths of 200 feet or more, the rhodochrosite is altered to oxides. Manganese carbonate veins at Butte also are mined for manganese.

The largest deposits of low-grade ferruginous manganese ore are in the Cuyuna range, Minnesota.[2] These deposits are the weathered outcrops of sedimentary beds. Deposits of manganese ore are found also in Arizona,[3] Arkansas,[4] Colorado,[5] Nevada,[6] New Mexico,[7] Utah,[8] Virginia,[9] and other States.

[1] EMMONS, W. H., and CALKINS, F. C.: Geology and Ore Deposits of the Philipsburg Quadrangle, Montana. U. S. Geol. Survey *Prof. Paper* 78, pp. 1–213, 1913.

[2] HARDER, E. C. and JOHNSTON, A. W.: Preliminary Report on the Geology of East Central Minnesota, Including the Cuyuna Iron-ore District. Minn. Geol. Survey *Bull.* 15, pp. 1–178, 1917.

[3] ALLEN, M. A. and BUTLER, G. M.: Manganese. Arizona University Bureau of Mines *Bull.* 91, 1918.

JONES, E. L. and RANSOME, F. L.: Deposits of Manganese Ore in Arizona. U. S. Geol. Survey *Bull.* 710, pp. 93–184, 1919.

[4] PENROSE, R. A. F., JR.: Manganese, Its Uses, Ores, and Deposits. Ark. Geol. Survey, Ann. Rept. for 1890, vol. 1, 1893.

MISER, H. D.: Manganese Deposits of Caddo Gap and De Queen Quadrangles, Arkansas. U. S. Geol. Survey *Bull.* 660, pp. 59–122, 1917.

[5] UMPLEBY, J. B.: Leadville Manganese Resources. *Min. and Sci. Press*, vol. 115, p. 758, 1917.

[6] PARDEE, J. T., and JONES, E. L., JR.: Deposits of Manganese Ore in Nevada. U. S. Geol. Survey *Bull.* 710, pp. 209–248, 119.

[7] JONES, E. L., JR.: Deposits of Manganese Ore in New Mexico. U. S. Geol. Survey *Bull.* 710, pp. 37–60, 1919.

[8] HEIKES, V. C.: Some Manganese Deposits in Central Utah. U. S. Geol. Survey *Bull.*—(in preparation).

[9] HEWETT, D. F.: Some Manganese Mines in Virginia and Maryland. U. S. Geol. Survey *Bull.* 640, pp. 37–71, 1916.

HEWETT, D. F., STOSE, G. W., KATZ, F. J. and MISER, H. D.: Possibilities for Manganese in Certain Undeveloped Tracts in the Shenandoah Valley, Virginia. U. S. Geol. Survey *Bull.* 660, pp. 271–296, 1918.

WATSON, T. L. and WHERRY, E. T.: Pyrolusite in Virginia. Wash. Acad. Sci., *Jour.*, vol. 8, pp. 550–560, 1918.

Probably the largest manganese deposits known are those on the southwest slopes of the Caucasus Mountains[1] in Russia. These deposits are of sedimentary origin and occur at the base of the Eocene in a flat-lying bed, below which is Cretaceous chalk. An area of about 22 square miles is probably underlain by good ore. The average thickness of the ore bed is 6 or 7 feet, and the total amount of ore present is estimated[1] at 110,000,000 metric tons.

In India[2] manganese ores are found at many places where sedimentary rocks of Archean age are deeply weathered. Manganese was present in the sedimentary rocks, and at places the rocks, by regional metamorphism, were converted into schists with manganese, garnet, and rhodonite. Prolonged weathering has resulted in their decay and in the concentration of manganese as oxides near the surface.

In Brazil manganese ores are found in several districts. The largest deposits are in the State of Minas Geraes, and the principal districts are Miguel Burnier and Lafayette. The ores occur in a complex of granite and crystalline schist and in overlying pre-Cambrian metamorphosed sediments. Where mining has gone deep enough to encounter the protore, rocks containing manganese silicates and carbonate are found. In some of the deposits the parent rock was evidently a manganese-rich igneous rock, and in others it was a manganese-rich sedimentary rock.[3]

The production of manganese ore (35 per cent. of manganese or more) in the United States in 1920 was 94,000 tons, valued at $2,385,000. The production of manganiferous ore (5 to 35 per cent. of manganese) was 673,000 tons, valued at $2,091,000.

[1] Beyschlag, F., Krusch, P. and Vogt, J. H. L.: Lagerstätten der nutzbaren Mineralien und Gesteine, *Band* 2, p. 591–595, 1913.

[2] Fermor, L. L.: The Manganese-ore Deposits of India. Geol. Survey India, *Mem.*, vol. 37, parts 1–3, pp. 1–610, 1909.

[3] Derby, O. A.: On the Manganese Ore Deposits of the Queluz (Lafayette) District, Minas Geraes, Brazil. *Am. Jour. Sci.*, 4th ser., vol. 12, pp. 19–23, 1901.

Branner, J. C.: The Manganese Deposits of Bahia and Minas Geraes, Brazil. Am. Inst. Min. Eng. *Trans.*, vol. 29, p. 756, 1899.

Harder, E. C., and Chamberlin, R. T.: Geology of Central Minas Geraes, Brazil. *Jour. Geol.*, vol. 23, pp. 341–378, 385–427, 1915.

Singewald, J. T., Jr., and Miller, B. L.: The Manganese Ores of the Lafayette District, Brazil. Am. Inst. Min. Eng. *Trans.*, vol. 56, pp. 7–30, 1916.

The principal uses of manganese are for making ferromanganese (Mn = 75 to 80 per cent.) and spiegeleisen (Mn = 12 to 20 per cent). These compounds, with carbon, are added to molten iron to improve the quality of steel. Manganese is used also for making other alloys, for making dry batteries, disinfectants, glass, colored brick, paints, chemicals, etc. It is used for flux in melting silver and gold ores. Manganese ores carrying less than 35 per cent. of manganese normally do not command high prices.

ALUMINUM AND BAUXITE

Minerals	Percentage of aluminum	Composition
Diaspore	45.0	$Al_2O_3 \cdot H_2O$
Gibbsite	34.6	$Al_2O_3 \cdot 3H_2O$
Bauxite	39.1	$Al_2O_3 2H_2O$
Alunite	19.6	$K_2O \cdot 3Al_2O_3 \cdot 4SO_3 \cdot 6H_2O$
Kaolin	20.9	$Al_2O_3 \cdot 2SiO_2 \cdot 2H_2O$
Sericite	20.4	$K_2O \cdot 3Al_2O_3 \cdot 6SiO_2 \cdot 2H_2O$
Corundum	52.9	Al_2O_3
Feldspars	....	Variable
Nepheline	17.6	$NaAlSiO_3$
Cryolite	12.8	Na_3AlF_6

Bauxite is the principal ore of aluminum, Diaspore and gibbsite are commonly present in bauxite ores. Alunite is utilized for the production of potash salts, and aluminum compounds are recovered as by-products. Patents have been issued for a process for the recovery of aluminum from kaolin, but the value of this process is problematical. Corundum is used as an abrasive. Kaolin, sericite, nepheline, and feldspars are protores of bauxite deposits.

The superficial concentration of bauxite is closely analogous to that of iron oxide. As iron is concentrated from dunite, peridotite, or greenalite and sideritic rocks, so bauxite is concentrated from nepheline syenite, clayey limestone, and other rocks rich in aluminum, especially from those that supply abundant alkalies to solutions removing silica.

The principal bauxite-producing areas in the United States are near Little Rock, Arkansas. The earliest description of the

region is that by Branner,[1] who discovered the deposits. Recently detailed explorations have been made by Mead.[2] The region is one of folded Paleozoic sedimentary rocks intruded by large bodies of nepheline syenite. These rocks were eroded and locally were extensively weathered. By weathering the syenite, which contains about 27 per cent. of alumina in silicates, was converted to bauxite ore, which contains about 37 to 57 per cent. of alumina as the hydrated oxide. The layer of ore, which has an average thickness of 11½ feet, grades downward into the syenite.

In Tertiary time, after extensive weathering and enrichment of the exposed surface of the syenite, the ore was eroded from the

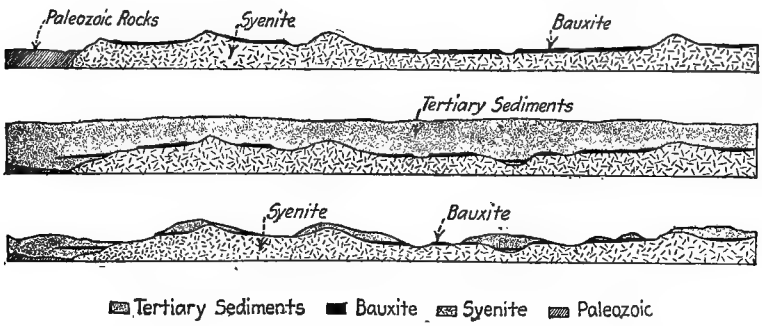


FIG. 254.—Generalized cross-sections illustrating geologic history of Arkansas bauxite deposits. (*After Mead.*)

syenite in places and was interstratified with Tertiary sediments near by. The deposits later were covered by the Tertiary sediments (Fig. 254), which at some places have not yet been removed by erosion.

In the southern Appalachian region, in a narrow belt[3] about 60 miles long, extending through Rome, Ga., and Rock River, Ala., bauxite deposits are found here and there in a residual

[1] BRANNER, J. C.: Bauxite in Arkansas. *Am. Geologist*, vol. 12, pp. 181–183, 1891.—The Bauxite Deposits of Arkansas. *Jour. Geol.*, vol. 5, pp. 263–289, 1897.

HAYES, C. W.: The Arkansas Bauxite Deposits. U. S. Geol. Survey *Twenty-first Ann. Rept.*, part 3, pp. 441–472, 1900.

[2] MEAD, W. J.: Occurrence and Origin of the Bauxite Deposits of Arkansas. *Econ. Geol.*, vol. 10, pp. 28–54, 1915.

[3] HAYES, C. W.: The Geological Relations of the Southern Appalachian Bauxite Deposits. Am. Inst. Min. Eng. *Trans.*, vol. 24, p. 243, 1894.

mantle, 100 feet or more thick, that rests on sedimentary rocks, mainly on the Knox dolomite.

Near Keenburg, Carter County, Tenn., bauxite is found as a large, irregular, deep pocket deposit in residual material resulting from the decomposition of the Knox dolomite.[1]

In Georgia, about 30 miles east of Macon, bauxite is mined from the Tuscaloosa (Lower Cretaceous) formation, which is made up chiefly of flat-lying unconsolidated clays and sands. The deposits were first described by Otto Veatch,[2] who discovered them, and later by Shearer.[3]

The bauxite deposits rest directly on the Cretaceous clays or occur as nodules disseminated through them. The beds are 10 feet thick or less.

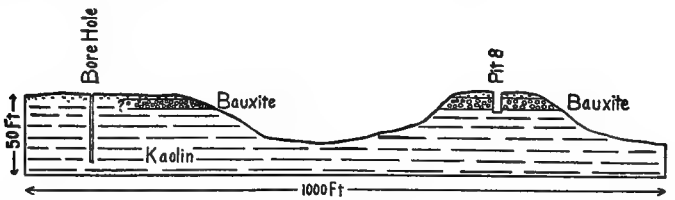


FIG. 255.—Section of bauxite deposit on Easterlin property, Sumpter County, Georgia. (*After Shearer.*)

The bauxite, according to Shearer, has resulted from the alteration of kaolin (Fig. 255) possibly through the agency of sulphate waters, which are known to have been present in Cretaceous time and which issue locally today in this region.

Aluminum is used in the manufacture of many articles where strength with lightness is required. Aluminum competes with copper as a conductor of electricity. It is used in the manufacture of alloys, chemicals, explosives, paints, etc.

Bauxite is used for the manufacture of aluminum and aluminum salts, including alundum, or fused alumina, which is used for an abrasive. Bauxite bricks are used for furnace linings.

The production of aluminum in the United States in 1920 was valued at $41,375,000. The production of bauxite in the United States in 1920 was 521,308 long tons, valued at $2,817,000.

[1] PHALEN, W. C.: Aluminum. U. S. Geol. Survey *Mineral Resources*, 1912, part 1, p. 951, 1913.

[2] VEATCH, OTTO: The Bauxite Deposits of Wilkinson County, Georgia. Ga. Geol. Survey *Bull.* 18, p. 430, 1909.

[3] SHEARER, H. K.: Bauxite and Fuller's Earth of the Coastal Plain of Georgia. Ga. Geol. Survey *Bull.* 31, pp. 123–132, 1917.

NICKEL

Mineral	Percentage of nickel	Composition
Garnierite	....	$H_2(NiMg)SiO_2 + H_2O$
Annabergite	29.4	$Ni_3As_2O_8 + 8H_2O$
Millerite	64.7	NiS
Niccolite	43.9	NiAs
Chloanthite	28.1	$NiAs_2$
Gersdorffite	35.4	NiAsS
Pentlandite	22.0	(Fe,Ni)S

The principal nickel deposits have been formed by magmatic segregation or by superficial concentration from basic rocks. Nickel minerals occur also in vein deposits. The gossan of nickeliferous pyrrhotite deposits is essentially limonite. If arsenic is present nickel forms with it annabergite which is frequently found at the very surface and may indicate the presence of a nickeliferous deposit below. Hydrous nickel-magnesium silicates also are stable, and garnierite forms valuable deposits where nickeliferous basic rocks are weathering. It is a common alteration product of nickeliferous olivine. There is good evidence of the deposition of secondary nickel sulphides, at least in small amounts. According to Kemp, secondary millerite was of economic value in the Lancaster Gap mine, Pennsylvania.

Pentlandite, which is probably primary in all occurrences, is the chief ore of nickel. It is found at Sudbury, Ontario, in deposits of sulphide ore formed by magmatic segregation, in which it is microscopically intergrown with pyrrhotite.

The United States produced 349 tons of nickel in 1920, valued at $275,120. The imports were valued at $10,857,657.

Sudbury, Ontario.—The nickeliferous rocks of Sudbury are included in an elliptical area some 40 miles long and 20 miles wide, whose longer axis strikes north of east.[1] The central por-

[1] BARLOW, A. E.: Report on the Origin, Geological Relations, and Composition of the Nickel and Copper Deposits of the Sudbury Mining District, Ontario. Canada Geol. Survey *Ann. Rept.*, vol. 14, part H, 1904.

COLEMAN, A. P.: The Sudbury Nickel Field. Ontario Bureau of Mines *Rept.*, vol. 14, part 3, p. 14, 1905.

ROBERTS, H. M., and LONGYEAR, R. D.: Genesis of the Sudbury Nickel-copper Ores as Indicated by Recent Explorations. Am. Inst. Min. Eng. *Trans.*, vol. 59, pp. 27–67, 1918.

tion of the ellipse has been eroded to a peneplain, which is surrounded by a hilly belt of eruptive rock. The oldest series in the region consists of Huronian sedimentary rocks which are intruded by acidic and basic rocks. The Upper Huronian rocks (Animikie group) include conglomerate, tuffs, slates, and sandstones. Intruded between the Lower Huronian rocks or their igneous intrusives and the Upper Huronian sedimentary rocks is the great laccolithic mass which contains the Sudbury nickel deposits. This great sheet dips toward its center, forming a canoe-shaped body which crops out in a rudely elliptical belt having a nearly plane surface. As a result of magmatic differentiation the lower portion of the laccolith is norite and the upper portion is micropegmatite, the two rocks grading into each other (p. 204).

The ore deposits include (1) those formed by magmatic segregation, which occur between the norite and the underlying rocks, (2) deposits of nearly related genesis in or near dikes of norite that extend outward from the lower contact of the main laccolithic body, and (3) deposits outside the laccolith, associated with norite intrusions, which possibly are connected with the principal body of the nickeliferous igneous rock beneath the surface. The ore consists chiefly of pyrrhotite, which contains small amounts of pentlandite and chalcopyrite. At many places it grades into pyrrhotitic norite. Other minerals are pyrite, magnetite, niccolite, cassiterite, gersdorffite, polydymite, danite, galena, sperrylite, and gold. The gangue includes the rock-making minerals of norite, with some quartz, calcite, and other carbonates. Some of the deposits, as shown by Knight, exhibit evidence of the presence of aqueous solutions at the time of their deposition.

Alexo, Ontario.—The Alexo nickel deposit, in Dundonald Township, northern Ontario,[1] is nickeliferous pyrrhotite that occurs along a contact of serpentinized peridotite and rhyolite. The ore minerals are pyrrhotite, pentlandite, magnetite, and chalcopyrite. Well-formed crystals of olivine are surrounded by a matrix of pyrrhotite. Pyrrhotite veinlets cut the serpentine, and pentlandite occurs as stringers in pyrrhotite. Uglow

[1] Uglow, W. L.: The Alexo Nickel Deposit, Ontario. Ontario Bureau of Mines *Twentieth Ann. Rept.*, part 2, p. 34, 1911.

Coleman, A. P.: The Alexo Nickel Deposit. *Econ. Geol.*, vol. 5, pp. 373–376, 1910.

believes that the deposit was formed by replacement from aqueous solution; Coleman considers it due to magmatic segregation.

Lancaster Gap, Pennsylvania.—At Lancaster Gap,[1] Pa., pyrrhotite ores occur in amphibolite which is inclosed in mica schist. The deposits were worked for nickel before the Sudbury ores were developed. The amphibolite, which is probably an altered norite, carries pyrrhotite and chalcopyrite. Kemp considers these deposits as formed by magmatic segregation from norite.

New Caledonia.—New Caledonia[2] is the world's most productive nickel-bearing region except the Sudbury district. The deposits cap serpentine and peridotite and are covered by ferruginous clay. The ores are segregated in flat-lying deposits, veinlets, and stockworks. They have evidently been concentrated by weathering from nickeliferous serpentine and peridotite. The principal minerals are garnierite and other nickel silicates.

Riddle, Oregon.—At Riddle,[3] Ore., nickel silicate ores are formed from weathering peridotite.

COBALT

Mineral	Percentage of cobalt	Composition
Erythrite (cobalt bloom)	29.4	$Co_3As_2O_8 \cdot 8H_2O$
Asbolite	32.0 ±	Oxides of cobalt and manganese
Jaspurite	64.7	CoS
Smaltite	28.2	$CoAs_2$
Cobaltite	35.5	CoAsS

Cobalt ores are found principally in veins and in surface concentrations from rocks formed by magmatic segregation. Cobalt oxidizes readily under conditions of weathering. Cobaltite and smaltite are primary, asbolite and erythrite are secondary.

Asbolite is a hydrated oxide of uncertain composition in which are oxides of manganese and cobalt, the latter in some specimens amounting to 32 per cent. In deposits in New

[1] KEMP, J. F.: The Lancaster Gap Nickel Mine. Am. Inst. Min. Eng. *Trans.*, vol. 24, p. 620, 1894.

[2] GLASSER, E.: Rapport sur les richesses minérales de la Nouvelle Calédonie. *Annales des mines*, 10th ser., vol. 5, pp. 503–701, 1904.

[3] KAY, G. F.: Nickel Deposits of Nickel Mountain, Oregon. U. S. Geol. Survey *Bull.* 315, p. 120, 1907.

Caledonia it is a decomposition product of serpentinized peridotite.[1] It was common in the deposits of the Mine La Motte area, Missouri.[2]

Cobalt is obtained as a by-product from refining silver, copper, or nickel ores. The silver ores of Cobalt, Ontario,[3] are rich in cobalt. Some cobalt is recovered from the Sudbury nickel ores. Nearly all the cobalt used in the United States is normally imported from Europe, where it is obtained principally from copper ores shipped from the Belgian Kongo,[4] some of which carry about 3.0 per cent. of cobalt. Cobalt is used for making alloys and pigments.

MERCURY

Mineral	Percentage of mercury	Composition
Native mercury, quicksilver	100.0	Hg
Calomel	84.9	HgCl
Cinnabar	86.2	HgS

Cinnabar is almost invariably primary; calomel and native mercury are generally secondary. Cinnabar is the only important primary ore of quicksilver.[5] It is almost everywhere associated with calcite, chalcedony, and quartz. Barite, marcasite, and pyrite are commonly present, as are also realgar, stibnite, and bituminous matter. Practically all mercury deposits of economic value are veins or nearly related deposits formed in the shallow vein zone.

The common association with igneous rocks and hot springs points to the agency of ascending hot waters. Many mercury deposits are of late Tertiary age.

[1] GLASSER, E.: Rapport sur les richesses minérales de la Nouvelle Calédonie. *Annales des mines*, 10th ser., vol. 5, pp. 503–701, 1904.

[2] KEYES, C. R.: A Report on the Mine La Motte Sheet. Mo. Geol. Survey *Rept.* 4, vol. 9, p. 82, 1895.

[3] MILLER, W. G.: The Cobalt-Nickel Arsenides and Silver Deposits of Temiskaming. Ontario Bureau of Mines *Rept.*, vol. 19, part 2, pp. 12, 17, 1913.

[4] BALL, S. H. and SHALER, M. K.: Mining in the Belgian Congo in 1913. *Min. and Sci. Press*, vol. 108, pp. 320–325, 1914.

[5] MCCASKEY, H. D.: U. S. Geol. Survey *Mineral Resources*, 1908, part 1, p. 683, 1909; also subsequent volumes.

BECKER, G. F.: Geology of the Quicksilver Deposits of the Pacific Slope. U. S. Geol. Survey *Mon.* 13, 1888.

The quicksilver deposits of California are in the Coast Range, extending northwest from a point near Santa Barbara about 400 miles to a point near Colusa. There are a few scattered deposits also in the north end of the State. This belt contains more than a score of districts that have yielded large amounts of quicksilver. The deposits are in rocks ranging in age from Mesozoic to Quaternary. Igneous rocks of Tertiary and Quaternary age are found at many places in this region: andesites, rhyolites, and basalts are present in many districts. The deposits are fissure veins, fractured zones, stockworks, or chambered breccia veins. They are found in metamorphic rocks, sandstones, tuffs, slates, serpentine, and gravel. In general the deposits decrease in size or give out in depth. In many of them operations ceased 300 or 400 feet below the surface. At the New Almaden mine, in Santa Clara County, however, the ore extended downward to the 1,600-foot level. The deposits were formed in late geologic time, near the surface at the time of deposition. Many of them are associated with hot springs.

The Terlingua district is in Brewster County, western Texas, near the Mexican border. Cretaceous limestone, shale, and marl are cut by Tertiary intrusives and in places are overlain by tuffs and flows. The ore is found in fractured zones and brecciated veins in limestone. As shown by Udden,[1] many of the deposits are found at the crests of anticlines. Calcite is the chief gangue mineral. Montroydite (HgO), terlinguaite (Hg_2ClO), and eglestonite (Hg_4Cl_2O), which have been identified only in this area, are probably decomposition products of cinnabar.

Deposits of cinnabar occur also in New Mexico, Nevada, Utah, and Oregon. The principal foreign deposits are in the Almaden district, Spain, and the Idria district, formerly in Austria, 28 miles from Trieste.

Mercury is recovered from its ores by distillation. It is used for making explosives, alloys, drugs, paints, and electric and other apparatus. Formerly large amounts of mercury were used in amalgamating silver ores, but this use has now decreased nearly to the vanishing point. Quicksilver is still used for amalgamation in many gold mills.

[1] Udden, J. A.. The Anticlinal Theory as Applied to Some Quicksilver Deposits. Texas University, Bureau of Econ. Geol. and Tech. 1822, Apr. 18, 1918.

In 1875 the United States produced mercury valued at $4,228,538. The production has declined in recent years, owing to lower prices, and also to the exhaustion of richer parts of the deposits. Stimulated by demand from manufacturers of explosives, however, the output was greatly increased during the World War. In 1920 the production was 13,070 flasks of 75 pounds, valued at $1,041,156

ANTIMONY

Mineral	Percentage of antimony	Composition
Native antimony	100.0	Sb
Cervantite	78.9	Sb_2O_4
Senarmontite	83.3	Sb_2O_3
Valentinite	83.3	Sb_2O_3
Bindheimite	.....	$Pb_3Sb_2O_8 + xH_2O$
Tetrahedrite	24.8	$4Cu_2S{\cdot}Sb_2S_3$
Jamesonite	29.5	$Pb_2Sb_2S_5$
Bournonite	24.7	$PbCuSbS_3$
Stibnite	71.4	Sb_2S_3

Stibnite is by far the most abundant ore of antimony. It occurs in quartz veins and related deposits formed chiefly at moderate and shallow depths. In weathering activities antimony minerals resemble those of lead; the metal tends to remain or accumulate in zones of oxidation.

Near Gilham, Sevier County, Ark.,[1] deposits of antimony occur in Paleozoic sandstones and shales. These rocks are thrown into folds and are cut by igneous intrusives. The ore deposits are thin tabular masses which generally follow the bedding planes.

The Arabia district, Nevada, is 4 miles west of Oreana, Humboldt County. The country rock is a mass of granodiorite that cuts through and metamorphoses sedimentary rocks. The deposits are fissure veins of the deep zone, the original ore evidently being composed of tourmaline, quartz, jamesonite, galena, and other minerals. Near the surface it has oxidized to

[1] Hess, F. L.: The Arkansas Antimony Deposits. U. S. Geol. Survey *Bull.* 340, pp. 241–252, 1908.

bindheimite,[1] cerusite, and plumbojarosite. The better grade ore carries 40 to 50 per cent. of antimony and lead, and 60 ounces of silver to the ton. The deposits had not been explored in depth in 1918.

Antimony is used for making "hard" lead, metal for bearings, and many other alloys, for drugs and paints, and for many other purposes. In antimony-lead ores it is recovered as antimonial lead, which is used for making type metal.

The production of antimony in the United States is small. Nearly all of the domestic supply comes from China, France, Algiers, Austria, and Mexico.

ARSENIC

Mineral	Percentage of arsenic	Composition
Native arsenic	100.0	As
Realgar	70.1	AsS
Orpiment	61.0	As_2S_3
Tennantite	17.0	$4Cu_2S \cdot As_2S_3$
Enargite	19.1	Cu_3AsS_4
Arsenopyrite	46.0	FeAsS

The commercially valuable deposits of arsenic are principally lodes formed at moderate depths. Arsenic minerals are common in many gold and copper ores, and arsenopyrite has been found at many places in the Appalachian region. At Brinton, Floyd County, Virginia, arsenopyrite deposits in mica schist are mined and the ore is calcined for white arsenic.[2] Arsenopyrite was mined for arsenic at Monte Cristo, Wash.

The greater part of the arsenic produced in the United States is a by-product from the gases of copper furnaces, particularly from plants smelting enargite ores of Butte, Mont., and Tintic, Utah. The fumes from the furnaces are conducted through a

[1] KNOPF, ADOLPH: The Antimonial Silver-lead Veins of the Arabia District, Nevada. U. S. Geol. Survey *Bull.* 660, p. 253, 1918.

HAGUE, J. D.: Mining Industry. U. S. Geol. *Expl. 40th Par. Rept.*, vol. 3, pp. 300–308, 1870.

[2] HESS, F. L.: The Arsenopyrite Deposits of Brinton, Va. U. S. Geol. Survey *Bull.* 470, p. 209, 1912.

WATSON, T. L.: "Mineral Resources of Virginia," p. 210, 1907.

labyrinth of chambers, on the walls of which arsenic oxide is deposited.

Arsenic and its compounds are used for making Paris green, drugs, alloys, poisons, dyes, and glass. Much arsenic is used with lead for hardening shot.

The production of arsenious oxide in the United States in 1920 was 11,502 short tons, valued at $2,021,356.

BISMUTH

Mineral	Percentage of bismuth	Composition
Native bismuth	100.0	Bi
Bismite, bismuth ocher	[a]89.6	Bi_2O_3 + aq
Bismutite	79.1	$Bi_2O_3 \cdot CO_2 \cdot H_2O$
Bismuthinite	81.2	Bi_2S_3
Tetradymite	51.9	$Bi_2(Te,S)_3$

[a] Percentage of bismuth in Bi_2O_3. The water present is variable.

Native bismuth and bismuth sulphides are primary; the oxides and carbonates are secondary. Bismuth compounds are relatively insoluble and alter very slowly.

Bismuth minerals are found in pegmatite veins and in some contact-metamorphic deposits, but the metal is derived mainly from lode ores of gold, silver, and copper. It is recovered principally from the muds obtained from refining blister copper. Although bismuth is present in small amounts in the ores of several western districts, the United States produces only a few thousand dollars' worth annually. The imports come normally from Germany and amount to about $300,000 a year.

Bismuth carbonate ore is mined at Engle, N. Mex.,[1] where it is associated with copper carbonates and scheelite. It has been mined also at Leadville, Colo.,[2] where it is associated with sulphides.[3] On the Mole Tableland, in northern New South Wales, bismuth ore is found in pegmatite veins.[4]

[1] HESS, F. L.: U. S. Geol. Survey *Mineral Resources*, 1908, part 1, p. 714, 1909.

[2] HESS, F. L.: *Idem*, 1912, part 1, p. 1043, 1913.

[3] EMMONS, S. F.: Geology and Mining Industry of Leadville, Colo. U. S. Geol. Survey *Mon.* 12, p. 377, 1886.

[4] CARNE, J. E.: The Tungsten Mining Industry in New South Wales. New South Wales Geol. Survey *Mineral Resources*, No. 15, pp. 68–71, 1912.

Bismuth is used for making plugs for automatic fire sprinklers, other fusible alloys, electrical fuses, solders, and glass and for toilet and medicinal preparations. The price is about $2 a pound.

MOLYDBENUM

The principal ore of molybdenum[1] is molybdenite (MoS_2). Other molybdenum minerals are wulfenite ($PbMoO_4$), molybdite (MoO_3), and a yellowish oxidation product, molybdic ocher (a hydrous ferric molybdate). Molybdenite is primary; the other minerals named are probably everywhere alteration products.

Molybdenite, though not abundant, is widespread. It is a constituent of some granites and pegmatites and of veins formed at great depths. It is found also in veins formed in the intermediate zone.

The largest molybdenite deposit in the United States is on Bartlett Mountain, Summit County, Colorado, where a great body of rock contains disseminated molybdenite. Considerable wulfenite has been obtained from the tailings of gold ore of Pinal County, Arizona. Small amounts of molybdenum ore have been found at many other places in the western part of the United States and in pegmatites in eastern Maine. In Canada[2] pegmatites contain molybdenite. Molybdenite deposits occur also in eastern Australia and in Norway.

Molybdenum is used in making hard steel and other alloys, permanent magnets and other electric apparatus, and chemicals, also for coloring porcelain green.

VANADIUM

Vanadium in small amounts is commonly present in igneous rocks. It occurs also in alteration products of many veins. It forms rather soluble salts and migrates readily in cold solutions.[3] The principal ores of vanadium in the United States are carnottite ($2U_2O_3 \cdot V_2O_5 \cdot K_2O \cdot 3H_2O$) and roscoelite ($AlV_2 \cdot KH_2 \cdot Si_9O_{24}$).

[1] PARSONS, A. L.. Molybdenite Deposits of Ontario. Ont. Bureau of Mines *Twenty-sixth Ann. Rept.*, pp. 275–313, 1917.

[2] WALKER, T. L.: Report on the Molybdenum Ores of Canada, p. 64, Canada Dept. Mines, Mines Branch 93, 1911.

THOMPSON, E.: A Pegmatite Origin of Molybdenite Ores. *Econ. Geol.* vol. 13, pp. 302–313, 1918.

[3] NOTESTEIN, F. B.: Some Chemical Experiments Bearing on the Origin of Certain Uranium-vanadium Ores. *Econ. Geol.*, vol. 13, pp. 50–64, 1918.

These ores occur in sandstone in southwestern Colorado and southeastern Utah. The deposits are mentioned above as uranium and radium ores.

Near Placerville, Colo.,[1] roscoelite, together with a little carnotite, cements grains of quartz sand of the La Plata. These deposits are worked for vanadium. In this district a vein which occupies a fault[2] carries vanadium and some uranium. Vanadium is found in copper ores in the Shattuck mine, Bisbee, Arizona, and vanadium minerals occur in the Yellow Pine district, Nevada. Deposits of vanadium at Minasragra, Peru,[3] are in Mesozoic sediments that are intruded by numerous dikes of eruptive rock. The principal vanadium deposit occupies a fault fissure, and the sulphide, patronite, is associated with coke and asphaltum.

The principal use of vanadium is for making a special steel, to which it gives increased hardness, toughness, and power to resist shock. It is used also in making copper alloys. Vanadium salts are used as mordants in dyeing, for drugs, and in many chemical preparations. The annual production in the United States is included with that of uranium.

URANIUM AND RADIUM

Carnotite..... $K_2O \cdot 2UO_3 \cdot V_2O_5 \cdot 8(?)H_2O$
Tyuyamunite..... $CaO \cdot 2UO_3 \cdot V_2O_5 \cdot 8(?)H_2O$
Torbernite..... $CuO \cdot 2UO_3 \cdot P_2O_5 \cdot 8H_2O$
Autunite..... $CaO \cdot 2UO_3 \cdot P_2O_5 \cdot 8H_2O$
Uvanite..... $2UO_3 \cdot 3V_2O_5 \cdot 15H_2O$
Pitchblende, an amorphous mineral containing uranium, rare earths, etc.
Gummite, hydrous uranium oxide with other bases.
Samarskite, of uncertain composition; contains uranium, iron, lime, and several rare earths.
Uraninite, crystalline variety of pitchblende.

Uranium minerals are found in veins associated with igneous rocks and disseminated in sandstone in regions where igneous activity is not prominent. Some of the uranium ores appear to have been deposited by cold water and enriched by superficial

[1] HILLEBRAND, W. F., and RANSOME, F. L.: On Carnotite and Associated Vanadiferous Minerals in Western Colorado. U. S. Geol. Survey *Bull.* 262, p. 14, 1905.

[2] HESS, F. L.: A Hypothesis for the Origin of the Carnotites of Colorado and Utah. *Econ. Geol.*, vol. 9, p. 681, 1914.

[3] HEWETT, D. F.: Vanadium Deposits of Peru. Am. Inst. Min. Eng. *Trans.*, vol. 40, p. 274, 1909.

alteration. The uranium ores are valuable for the radium they contain. Deposits are found in Colorado and Utah. In 1919 the production of uranium, vanadium, and radium ores in the United States amounted to $2,363,500.

The best-known deposits of uraninite or pitchblende are in the Erzgebirge, Bohemia and Saxony,[1] and in Gilpin County, Colorado. In the Erzgebirge sedimentary and metamorphic rocks are intruded by granitic rocks. At Joachimsthal, Bohemia, the pitchblende ores are associated with quartz, dolomite, pyrite, and chalcopyrite.

At Quartz Hill, Gilpin County, Colorado, schists and granites are cut by Tertiary intrusive monzonite and porphyries. Bastin[2] states that the pitchblende ore was deposited during the early pyrite mineralization and that it was subsequently fractured and veined with lead-zinc ores.

Uraninite is found in pegmatites in North and South Carolina, where it is largely altered to gummite and other minerals.

The largest deposits of uranium are in Paradox Valley,[3] Colorado, and in eastern Utah, where carnotite ore is found in fractures in Jurassic sandstone. The ore replaces calcite cement and organic material in the sandstone. In general the deposits are richer near the surface than in depth, and they are believed to have been concentrated by surface agencies.

Radium salts obtained from uranium ores are used for making objects luminous and in medicine, especially in the treatment of cancer.

TIN

Mineral	Percentage of tin	Composition
Cassiterite	78.6	SnO_2
Stannite	27.5	Cu_2FeSnS_4

[1] MÜLLER, HERMANN: Die Erzgänge des Annaberger Bergrevieres. Erläuterung zur Specialkarte des Königreichs Sachsen, p. 66, Leipzig, 1894.

[2] BASTIN, E. S.: Geology of the Pitchblende Ores of Colorado. U. S. Geol. Survey *Prof. Paper* 90, pp. 1–5, 1914.

[3] HILLEBRAND, W. F., and RANSOME, F. L.: On Carnotite and Associated Vanadiferous Minerals in Western Colorado. U. S. Geol. Survey *Bull.* 262, pp. 9–31, 1905.

HESS, F. L.: Notes on the Vanadium Deposits near Placerville, Colo. U. S. Geol. Survey *Bull.* 530 pp. 142–156, 1913.

Cassiterite[1] is found sparingly distributed in some igneous rocks and is a constituent of some pegmatites and of a few contact-metamorphic deposits. It occurs also in many veins, nearly all of which are of deep-seated origin (see page 281). Stannite is found in many deposits in Bolivia, particularly at Potosi.[2] Both stannite and cassiterite are almost insoluble in ground water; consequently tin deposits are enriched near the surface when other minerals are removed by solution. Much tin is obtained from placers. The tin deposits of the United States are small.

In the Carolina tin belt,[3] which extends from Gaffney, S. C., nearly to Lincolntown, N. C., cassiterite occurs in pegmatite, which is characterized by abundant muscovite, quartz, and a little plagioclase feldspar.

At Silver Hill, about 8 miles southeast of Spokane, Wash.,[4] and at the Etta mine, South Dakota,[5] cassiterite is found in pegmatite dikes. On Lost River, Seward Peninsula, Alaska, where granite intrudes limestone, a contact zone is developed, in which some cassiterite is found. Cassiterite is also found in this region in granite and in quartz veins.[6] Tin veins are found in the Franklin Mountains, Texas,[7] about 12 miles north of El Paso.

In the Temescal tin district, in western Riverside County, California, the tin deposits are veins in granite. The district has produced some tin, but the mine is now closed. The vein matter is dark tourmaline, high in iron and quartz, with which cassiterite is associated. Arsenopyrite and copper minerals are reported. The tin oxide is distributed either through the vein matter or in

[1] FERGUSON, H. G., and BATEMAN, A. M.: Geologic Features of Tin Deposits. *Econ. Geol.*, vol. 7, pp. 209–262, 1912.

[2] WENDT, A. F.: The Potosi, Bolivia, Silver Districts. Am. Inst. Min. Eng. *Trans.*, vol. 19, p. 90, 1891.

RUMBOLD, W. R.: The Origin of the Bolivia Tin Deposits. *Econ. Geol.*, vol. 4, p. 321, 1909.

[3] GRATON, L. C.: The Carolina Tin Belt. U. S. Geol. Survey *Bull.* 260, p. 191, 1905.

[4] COLLIER, A. J.: Tin Ores at Spokane, Wash. U. S. Geol. Survey *Bull.* 340, pp. 295–305, 1908.

[5] HESS, F. L.: Tin, Tungsten, and Tantalum Deposits of South Dakota. U. S. Geol. Survey *Bull.* 380, pp. 131–163, 1901.

[6] KNOPF, ADOLPH: Geology of the Seward Peninsula Tin Deposits. U. S. Geol. Survey *Bull.* 358, p. 23, 1908.

[7] RICHARDSON, G. B.: Tin in the Franklin Mountains, Texas. U. S. Geol. Survey *Bull.* 285, pp. 146–149, 1906.

stringers and bunches. The average of the ore milled contained about 5 per cent of the oxide.

Tin is used for plating steel, iron, and other metals, and for making tin ware, tinfoil, and bronze and other alloys. The production of tin in the United States in 1920 was 20 tons, valued at $20,100. The chief sources of tin are the Malay Peninsula and the islands of Banka and Billiton, near by, where the principal deposits are placers, and the lode deposits of Bolivia and Cornwall.

TUNGSTEN

Mineral	Percentage of WO_3	Composition
Tungstite	100.0	WO_3
Ferberite	76.3	$FeWO_4$
Wolframite	76.4	$(Fe, Mn)WO_4$
Hübnerite	76.6	$MnWO_4$
Scheelite	80.6	$CaWO_4$
Tungstenite	....	WS

Tungsten minerals are found in igneous rocks, in pegmatites, in contact-metamorphic deposits, and in veins associated with igneous rocks and formed at all depths. Tungsten deposits are probably not formed by cold solutions. Sulphuric acid attacks tungsten minerals slowly,[1] but the compounds formed break down into insoluble oxide; consequently there is little if any enrichment of tungsten deposits by solution and precipitation. On the contrary, valuable placer deposits of tungsten ores are formed. The principal ore minerals of tungsten are ferberite, wolframite, and hübnerite. These minerals form isomorphous compounds, the gravity changing with the composition. As shown by Runner,[2] the composition of the mineral may be estimated by accurate determination of its specific gravity. Most of the tungsten deposits of the United States are veins and contact-metamorphic deposits.

At Atolia, San Bernardino County, California, in an area of

[1] GANNET, R. W.: Experiments Relating to Enrichment of Tungsten Ores. *Econ. Geol.*, vol. 14, pp. 68–78, 1917.

[2] RUNNER, J. J., and HARTMANN, M. L.: The Occurrence, Chemistry Metallurgy, and Uses of Tungsten, with Special Reference to the Black Hills of South Dakota. South Dakota School of Mines *Bull.* 12, pp. 4–159, 1918.

schists cut by granite, scheelite is found in gold-bearing quartz veins.[1] Locally, in that region, sands and residual surface material have been worked as placers. Hübnerite and wolframite placers are worked in the Little Dragoon Mountains, Arizona.[2]

In Boulder County, Colorado,[3] the principal tungsten ore is ferberite, which occurs in small veins in granite. The ferberite resists weathering and forms placers. In the Black Hills bedding-plane deposits of wolframite replace flat-lying calcareous beds where the latter are crossed by thin fissures.

During the World War, when there was a great demand for tungsten, many deposits were found in Nevada and Utah. Prominent among them are contact-metamorphic deposits of scheelite replacing limestone near intrusive rocks.

The greatest output of tungsten ore at present comes from Asia, especially from China and Burma. In Burma the industry centers about Tavoy, where there are valuable veins in and near granite.[4] Spain, Portugal, Bolivia, Korea, and Tasmania produce noteworthy amounts.

Tungsten is used for making high-speed tool steel and other alloys and electric-light filaments, for coloring glass, and for fire-proofing textiles.[5]

Tungsten minerals are recovered from tungsten ores by mechanical concentration. In 1920 the United States produced 216 tons of concentrates (contents equivalent to 60 per cent. WO_3) valued at $77,760.

CHROMIUM

The principal ore of chromium is chromite, $FeCr_2O_4$ (Cr_2O_3 = 68 per cent.). This mineral is a common constituent of basic

[1] Hess, F. L.: U. S. Geol. Survey *Mineral Resources*, 1909, part 1, p. 734, 1910.

[2] Rickard, Forbes: Notes on Tungsten Deposits of Arizona. *Eng. and Min. Jour.*, vol. 78, p. 263, 1904.

[3] George, R. D.: The Main Tungsten Area of Boulder, Colorado. Colo. Geol. Survey *Ann. Rept.* for 1908, pp. 7–103, 1909.

Lindgren, Waldemar: Some Gold and Tungsten Deposits of Boulder County, Colorado. *Econ. Geol.*, vol. 2, pp. 453–463, 1907.

Hess, F. L., and Schaller, W. T.: Colorado Ferberite and the Wolframite series. U. S. Geol. Survey *Bull.* 583, 1914.

[4] Campbell, J. M.: Tungsten Deposits of Burma and Their Origin. *Econ. Geol.*, vol. 15, pp. 511–534, 1920.

[5] Hess, F. L.: Tungsten Minerals and Deposits. U. S. Geol. Survey *Bull.* 652, pp. 1–85, 1917.

igneous rocks, such as olivine gabbro, peridotite, and pyroxenite, in which it occurs as disseminated grains, as ill-defined streaks, and segregated in irregular masses. Peridotite and pyroxenite alter readily to serpentine, and much chromic iron ore is derived from serpentine. Chromite alters very slowly, and when serpentine bodies are weathered it may collect in gravel deposits or placers.

The largest deposits of chromic iron ore are in Rhodesia, Turkey, New Caledonia, and Greece. Chromite is widely distributed in areas of serpentine and other basic rocks in various parts of the United States. Such rocks are found at a few localities in the crystalline region east of the Appalachian Moun-

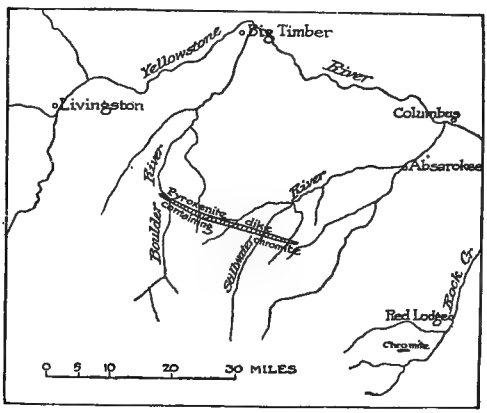


FIG. 256.—Sketch showing chrome ore belt of Boulder River and Rock Creek, Montana. (*After L. G. Westgate, U. S. Geol. Survey.*)

tains and at many places in the Sierra Nevada and Coast Range in California.

Chrome ores are found in Maryland[1] and in Pennsylvania,[2] where the Wood mine, in Lancaster County, was worked to a depth of 720 feet. Chrome sands were washed near the mine and in Maryland. In North Carolina chromium ore is found near the borders of peridotite masses, where, according to Pratt and Lewis,[3] it has segregated from the basic magma. Chromite

[1] SINGEWALD, J. T., JR.: Maryland Sand-chrome Ore. *Econ. Geol.*, vol. 14, pp. 189–197, 1919.

[2] GLENN, W.: Chrome in the Southern Appalachian Region. Am. Inst. Min. Eng. *Trans.*, vol. 25, pp. 481–489, 1895.

[3] PRATT, J. H., and LEWIS, J. V.: Corundum and the Peridotites of Western North Carolina. North Carolina Geol. Survey, vol. 1, pp. 1–461, 1905.

occurs in serpentine 16 miles southwest of Glenrock, Wyoming. Chrome ore occurs in a pyroxene (enstatite) dike south of Big Timber, Montana, where ores composed of chromite and magnetite appear to have been intruded in the pyroxene. This dike (Fig. 256) is 30 miles long and carries chrome ore at many

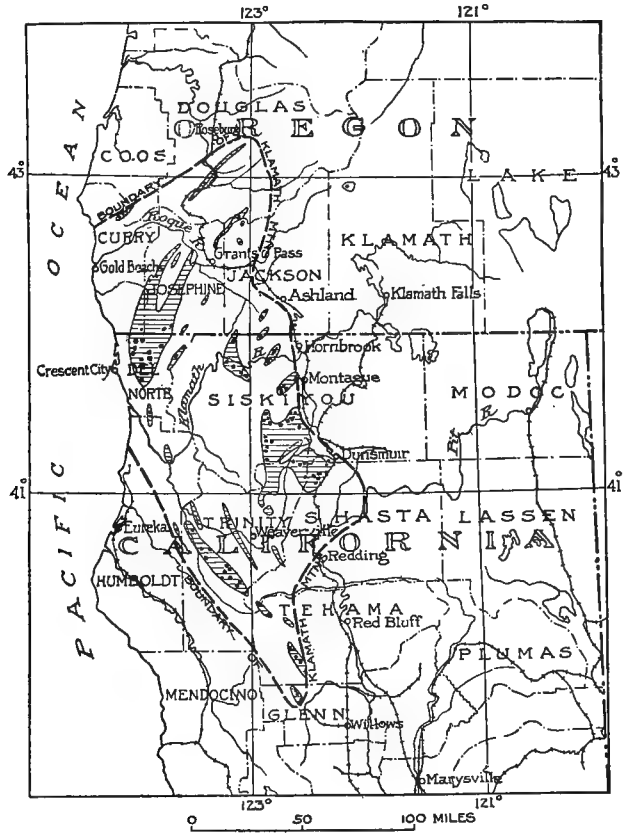


FIG. 257.—Map of the Klamath Mountains showing location of serpentine areas (horizontally ruled) and chromite deposits (dots). (*After Diller, U. S. Geol. Survey.*)

places. Most of the chromium deposits are near the center of the dike. The largest band of chromite ore is 13 inches wide. The ore reserves are large, but the ore must be concentrated to be marketed.

Chromite ore is mined at many places in Washington, Oregon, and California.[1] On Cypress Island, Washington, chrome ore is mined from serpentine, in which it occurs as stringers and grains. In Oregon it is mined in Grant, Josephine and other counties. In Grant County it occurs at many places in the Blue Mountains; most of the deposits are in streaks, lenses, and irregular masses in shattered serpentine. In 1918 Grant County produced 14,401 tons. In the Klamath Mountains, southwestern Oregon, and northwestern California, serpentine bodies cover wide areas. In this area chrome ore is found at many places,[2] all of them in serpentine (Fig. 257). In 1918 California produced 70,636 tons of chrome ore.

Chrome ores are mined from deposits in olivine rocks on Kenai Peninsula, Alaska.[3]

Chrome ore is used principally as a refractory material in open-hearth steel furnaces and for making refractory brick. Chromium is used for hardening steel and for the manufacture of chemicals and paints. Chromium salts are used in printing, dyeing, tanning leather, etc. The marketable ore generally carries 40 per cent. Cr_2O_3 or more. The United States produced 2,502 long tons of chromite ore in 1920 valued at $44,113.

PLATINUM

Platinum generally contains small amounts of other metals of the platinum group—iridium, osmium, palladium, rhodium, and ruthenium. These metals are closely associated in nature, almost invariably as native alloys. Two other minerals of the platinum group are sperrylite ($PtAs_2$) and laurite (RuS_2). Platinum is found in basic igneous rocks, such as peridotites and dunites, and in serpentine derived by alteration of such rocks. By disintegration of these rocks and concentration in stream gravels, platinum accumulates in placers. Nearly all of the world's

[1] Diller, J. S.: Recent Studies in Domestic Chromite Deposits. Am. Inst. Min. Eng. *Trans.*, vol. 63, pp. 105–149, 1920.

[2] Diller, J. S.: *Op. cit.*, p. 2026.

Harder, E. C.: Some Chromite Deposits in Western and Central California. U. S. Geol. Survey *Bull.* 430, p. 180, 1910.

[3] Gill, A. C.: Preliminary Report on the Chromite of Kenai Peninsula. U. S. Geol. Survey *Bull.* 712–D, pp. 99–129, 1919.

supply comes from the placers in the Ural Mountains[1] and in Colombia. Practically all the platinum produced in the United States is derived from black sand in California and Oregon and by refining the mud that forms in vats where blister copper is purified electrolytically. Platinum and palladium are found with gold in ores of the Boss mine, in the Yellow Pine district, Clark County, Nevada.[2]

Platinum is used for making chemical utensils, for jewelry, in dentistry, and for coating asbestos wool to be used in the contact process for making sulphuric acid. The United States produced 41,544 troy ounces of platinum and allied metals in 1920, valued at $4,697,722. Much of this was derived from Canadian nickel matte.

TANTALUM

The principal minerals of tantalum are tantalite ($FeTa_2O_6$) and samarskite, a complex tantalate of several rare metals. Tantalum minerals are found in pegmatite veins in the Black Hills, South Dakota,[3] and at a few places in the Appalachian region of the United States. Many foreign occurrences are known.

Tantalum has been used for filaments of incandescent lights, but tungsten has almost completely superseded it. Like platinum, it is little affected by many chemical reagents, and in the future it may be used instead of platinum to some extent in chemical laboratories.

TITANIUM

The principal titanium minerals are ilmenite ($FeTiO_3$) and rutile (TiO_2). Ilmenite is a rock-making mineral and is a common constituent of titaniferous magnetite[4] which has been formed

[1] PURINGTON, C. W.: The Platinum Deposits of the Jura River System, Ural Mountains, Russia. Am. Inst. Min. Eng. *Trans.*, vol. 29, pp. 3–16, 1899.

LINDGREN, WALDEMAR: Platinum and Allied Metals. U. S. Geol. Survey *Mineral Resources*, 1911, part 1, p. 987, 1912.

[2] KOPF, ADOLPH: A Gold-Platinum-Palladium Lode in Southern Nevada. U. S. Geol. Survey *Bull.* 620, pp. 1–18, 1915.

[3] HESS, F. L.: Tin, Tungsten, and Tantalum Deposits of South Dakota. U. S. Geol. Survey *Bull.* 380, pp. 131–163, 1909. U. S. Geol. Survey *Mineral Resources*, 1908 and later years.

[4] SINGEWALD, J. T.: The Titaniferous Iron Ores of the United States, Their Composition and Economic Value. U. S. Bureau of Mines *Bull.* 64, 1913.

at many places by magmatic segregation (see page 201). Because of metallurgical difficulties titaniferous ores are not much used, notwithstanding the fact that titanium increases the strength of steel.

Near St. Urbain, Quebec,[1] about 60 miles east of the city of Quebec, large masses of rock containing titanic iron are inclosed in anorthosite. These rocks in the main consist of ilmenite and hematite, with andesine, green spinel, and biotite. A considerable portion of one of these masses contains about 15 per cent. of rutile.

The rutile rock forms sharply defined portions of the ilmenite rock and represents a part of the segregation exceptionally rich in titanic oxide, magnesia, and alumina and deficient in silica.

Rutile is found at many places in the United States and has been exploited in the Magnet Cove region of Arkansas and in Nelson County, Virginia.[2] In the Virginia region a biotite gneiss, probably pre-Cambrian, is cut by great pegmatite dikes composed of feldspar, quartz, apatite, hornblende, and rutile. The pegmatites are cut by smaller dikes composed mainly of rutile and apatite. One of these, from a few inches to 5 feet thick, may be followed for half a mile or more. Much of the rutile carries iron.

Titanium and its compounds are used for coloring various products, for hardening steel, and for electric and other purposes. In 1919 the United States produced 102 tons of rutile, valued at $20,400.

CADMIUM

Cadmium sulphide, greenockite, is found in the Joplin region, Missouri, as a yellow powder coating crevices,[3] and the sphalerite of this region carries 0.4 per cent. or more of cadmium. Some other zinc ores and some lead ores contain small percentages of cadmium. The cadmium produced in the United States is obtained partly from treatment of bag-house products of smelters and as a by-product in the manufacture of zinc chloride. When zinc sulphide is heated with carbon in a retort, the cadmium

[1] WARREN, C. H.: The Ilmenite Rocks near St. Urbain, Quebec. A New Occurrence of Rutile and Sapphirine. *Am. Jour. Sci.*, vol. 33, ser. 4, pp. 263–277, 1912.

[2] WATSON, T. L.: The Occurrence of Rutile in Virginia. *Econ. Geol.*, vol. 2, p. 493, 1907.

[3] SIEBENTHAL, C. E.: U. S. Geol. Survey *Mineral Resources*, 1908, part 1, p. 793, 1909.

comes off at a lower temperature than the zinc, and by fractional distillation a concentration is effected. This method is used for recovering cadmium in Germany. Cadmium is not rare, but it is a comparatively unimportant metal in the arts. In the United States 129,283 pounds, valued at $151,261, was produced in 1920.

Metallic cadmium is used for making amalgams and alloys, and salts of cadmium are used in photography, in medicine, and in electroplating. The sulphide forms the basis of a high-grade yellow paint.

SELENIUM

Selenium in small amounts is found in some gold, silver, lead, and copper ores. It is commonly associated with tellurium in ores of precious metals. Appreciable quantities are present in ores of Tonopah, Nev., Republic, Wash., and Waihi, New Zealand.

Some of the bullion of the Donok mine, of the Lebongstreek, Sumatra, carries over 4 per cent of selenium. No tellurides are recognized in the ore of this mine.

Selenium is used[1] for making red gloss enamels, and glazes. Because its electric conductivity varies with the intensity of light it has many unique applications is making electric apparatus. Some selenium is obtained from the anode muds resulting from the electrolytic refining of copper. Selenium sells for about $2.50 a pound.

TELLURIUM

Tellurium, which is in the sulphur group, is closely allied also with some of the metals. It is found with native sulphur in Japan and is combined with gold, bismuth, and other metals in many vein deposits, especially in those of the late Tertiary group. In the United States it is most abundant in the gold deposits of Cripple Creek, Colo. It is generally present in small amounts in muds obtained in the electrolytic refining of copper. Tellurium is at present unimportant in the arts.

[1] HESS, F. L.: U. S. Geol. Survey *Mineral Resources*, 1908, part 1, pp. 715–717, 1909.

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